realities of energy systems. Experts in those subjects have a responsibility to communicate their understanding to non-experts clearly, completely, and without bias.

The GCRA mandate for the NCA does not include energy policy, although addressing the impact of warming temperatures and extreme weather on electricity demand and renewable energy resources arguably falls under the purview of GCRA mandate. Further, the NCA5 author list did not include the appropriate expertise in energy systems or analyses to justify their focus on energy policy and in particular wind and solar power.

On Sat, Jul 5, 2025 at 10:25 AM Steven Koonin <steven.koonin@gmail.com> wrote:

> My proposed revision of the debated text in Section 1.3 is attached.
>
> Also attached is a very recent CRS report on USGCRP that might be on interest (and is cited in the proposed revision).
>
> SEK

--

Judith Curry, President
CFAN - Climate Forecast Applications Network
Reno, NV USA
curry.judith@cfanclimate.com | +1.404.803.2012
http://www.cfanclimate.net

From: Judith Curry <curry.judith@gmail.com>
Sent: Saturday, July 5, 2025 1:59 PM
To: Steven Koonin
Cc: Roy W. Spencer; John Christy; Ross McKitrick; Travis Fisher; Josh Loucks; Cohen, Seth
Subject: Re: Debated text in 1.3

Hi Steve, interesting context from CRS.

I don't think your new text for 1.3 helps. I particularly don't like "stay in your lane," one might ask what is Steve Koonin's lane. The issue is commenting on energy policy is outside of the scope of the USGCRP mandate. Yes NCA can talk about warmer temperatures requiring more electricity, etc and hurricanes and floods can cause power outages. But that is different from advocating for Net Zero, wind and solar power, etc.

Try this:

When science is assessed for the purpose of climate policymaking there are further requirements to bear in mind. Good climate and energy policies should balance the risks and benefits of a changing climate against the world's growing demand for reliable and affordable energy. To strike that balance, policymakers must understand at least two complex and nuanced topics: the certainties and uncertainties of climate science and the technoeconomic realities of energy systems. Experts in those subjects have a responsibility to communicate their understanding to non-experts clearly, completely, and without bias.

The GCRA mandate for the NCA does not include energy policy, although addressing the impact of warming temperatures and extreme weather on electricity demand and renewable energy resources arguably falls under the purview of GCRA mandate. Further, the NCA5 author list did not include the appropriate expertise in energy systems or analyses to justify their focus on energy policy and in particular wind and solar power.

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Sent: Saturday, July 5, 2025 1:25 PM
To: 'Judith Curry'; 'Roy W. Spencer'; 'John Christy'; 'Ross McKitrick'
Cc: 'Travis Fisher'; 'Josh Loucks'; 'Cohen, Seth'
Subject: Debated text in 1.3
Attachments: Debated text 1.3.docx; CRS on USGCRP.pdf

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SEK

ORIGINAL

When science is assessed for the purpose of climate policymaking there are further requirements to bear in mind. Good climate and energy policies should balance the risks and benefits of a changing climate against the world's growing demand for reliable and affordable energy. To strike that balance, policymakers must understand at least two complex and nuanced topics: the certainties and uncertainties of climate science and the technoeconomic realities of energy systems. Experts in those subjects have a responsibility to communicate their understanding to non-experts clearly, completely, and without bias.

Much expertise in energy systems resides in the private sector, where it is essential to providing the reliable and affordable energy services that are the lifeblood of society. Understanding is therefore continually refined and tested by operational demands and the discipline of the marketplace. In contrast, climate science expertise is found largely in the non-profit realm of universities and government laboratories and so has a more academic character, with greater uncertainties and hence need for expert judgement.

For those reasons assessments of climate science that will be influential for policy making must include statements about the strength of knowledge. ...

PROPOSED REVISION

There are further requirements to bear in mind in scientific assessments that inform climate policymaking. Policymakers must understand at least two complex and nuanced topics: the certainties and uncertainties of climate science and the technoeconomic realities of energy systems. Beyond communicating their expertise transparently and without bias, experts in those distinct subjects have a responsibility to "stay in their lane." In that light, NCA5's statements on energy technologies (such as those in its Chapter 32) are advocacy and out of scope, as USGCRP supports little, if any, energy work (CRS 2025), nor do its authors appear to have much expertise in that domain.

[CRS 2025: https://www.congress.gov/crs_external_products/R/PDF/R48478/R48478.13.pdf]

Because there are significant uncertainties, and hence the need for expert judgement, in understanding how the climate responds to growing human influences, assessments of climate science must include statements about the strength of knowledge. ...

U.S. Global Change Research Program (USGCRP): Overview and Considerations for Congress

Updated July 2, 2025

Congressional Research Service
https://crsreports.congress.gov
R48478

CRS REPORT
Prepared for Members and
Committees of Congress

DOJ_00000506

Congressional Research Service
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SUMMARY

R48478

July 2, 2025

Kathryn G. Kynett
Analyst in Environmental Policy

U.S. Global Change Research Program (USGCRP): Overview and Considerations for Congress

The U.S. Global Change Research Program (USGCRP) is an interagency program established by Congress through the Global Change Research Act of 1990 (GCRA; P.L. 101-606) to coordinate and integrate federal research on global change. *Global change* refers to global environmental changes in Earth's climate, land productivity, water resources, atmospheric chemistry, and ecological systems that may affect Earth's capacity to sustain life. USGCRP was established to enhance scientific understanding of global changes and assess their potential impacts, and for the program's results be useful for those developing policy responses.

According to the USGCRP website, accessed on June 10, 2025, "[t]he operations and structure of the USGCRP are currently under review." On July 2, 2025, the website is inactive. As the Trump Administration looks to alter USGCRP and activities related to climate change, an issue for the 119th Congress may be whether—and if so, how—to alter congressional direction and funding for USGCRP and its activities.

Pursuant to the GCRA, USGCRP coordinates global change research conducted by the federal government, undertakes scientific assessments, and facilitates international scientific cooperation. To accomplish this, USGCRP coordinates U.S. global change research activities across 15 federal agencies and departments. The program produces reports and assessments, including a mandated periodic assessment synthesizing the findings of the program, observed and projected trends in global change, and the effects of global change across various sectors. To meet this mandate, USCGRP has periodically produced the National Climate Assessment (NCA). USGCRP supports U.S. participation in international scientific initiatives, including the Intergovernmental Panel on Climate Change (IPCC). U.S. scientists have played a prominent role in authoring, reviewing, and providing technical input for IPCC assessments.

USGCRP member agencies fund and implement global change research activities, with appropriations provided directly to the member agencies rather than through a centralized USGCRP budget. USGCRP compiles a budget crosscut in its annual reports, summarizing funding that agencies self-identify as their contributions to the program. Reported funding for USGCRP-related activities has increased since the program began; reported funding was approximately $4 billion in FY2023. (FY2023 is the last year for which USGCRP-related funding has been reported.)

Presidential Administrations and Congress have taken varying positions on the program. President Biden issued Executive Order (E.O.) 14072 directing USGCRP to develop an assessment on the "condition of nature within the United States." Pursuant to E.O. 14072, USGCRP began to develop a National Nature Assessment. In 2025, President Trump issued E.O. 14154 revoking E.O. 14072, and work on the National Nature Assessment was reportedly discontinued. In April 2025, the federal contract supporting USGCRP's National Coordination Office—which facilitated USGCRP's interagency and international coordination—was reportedly canceled. Federal staff previously involved in the program have reportedly been dismissed or are no longer working on USGCRP activities.

Members of Congress have also expressed a range of views regarding the program. For example, some Members have proposed restricting its funding, while other Members have proposed expanding the program's scope through new activities related to climate resilience. Congress may evaluate USGCRP's role under the GCRA, including whether it should remain the primary federal entity responsible for coordinating global change research, producing scientific assessments, and supporting international collaboration. Congress may also evaluate the future of USGCRP's scientific assessments, including the development of the Sixth National Climate Assessment (NCA6) and the extent of U.S. participation in international scientific assessments.

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Contents

Introduction 1
History, Functions, and Structure 2
Member Agencies and Departments 4
Budget Information 5
Interagency Groups 6
Scientific Assessments 7
    National Climate Assessment 7
    National Nature Assessment 8
International Coordination and Research 9
Considerations for Congress 10

Tables

Table 1. Crosscut by Agency for Expenditures in Support of USGCRP, Selected Years, Inflation-Adjusted 2023 Dollars 6

Contacts

Author Information 12

DOJ_00000508

Introduction

The U.S. Global Change Research Program (USGCRP) is an interagency program established by Congress in 1990 to coordinate and integrate federal research on global environmental changes, including climate change. According to the Global Change Research Act of 1990 (GCRA; Title I, P.L. 101-606), the program and its activities are to advance global change research and provide scientific information that is useful for policymakers.[1] To accomplish its functions pursuant to the GCRA, USGCRP serves as a platform for interagency coordination by facilitating meetings, supporting interagency groups, and developing strategic plans that establish research priorities. USGCRP produces scientific assessments, and it has released the National Climate Assessment (NCA)—which evaluates climate-related risks and impacts in the United States—approximately every four years. USGCRP facilitates U.S. participation in international global change research activities, including international scientific assessments, such as those conducted by the Intergovernmental Panel on Climate Change (IPCC).

USGCRP member agencies fund and implement global change research activities, with appropriations provided directly to the individual member agencies themselves rather than through a centralized USGCRP budget. USGCRP compiles a budget crosscut in its annual reports, referred to as *Our Changing Planet*, summarizing funding that agencies self-identify as their contributions to the program. Reported funding for USGCRP-related activities has increased since the program began; reported funding was approximately $4 billion in FY2023. (FY2023 is the last year for which USGCRP-related funding has been reported.)

Presidential Administrations and Congress have taken varying positions on the program. The Biden Administration issued Executive Order (E.O.) 14072 directing USGCRP to develop a new report on the status of the nation's natural resources—referred to as the National Nature Assessment.[2] In 2025, the Trump Administration issued E.O. 14154, which revoked E.O. 14072; USGCRP reportedly discontinued work on the National Nature Assessment after E.O. 14154.[3] According to the USGCRP website, accessed on June 10, 2025, "[t]he operations and structure of the USGCRP are currently under review."[4] On July 2—the date of publication of this report—the website is inactive. In April 2025, news organizations reported that the federal contract

[1] 15 U.S.C. §§2931-2938.

[2] Executive Order 14072 of April 22, 2022, "Strengthening the Nation's Forests, Communities, and Local Economies," 87 *Federal Register* 24851, April 27, 2022.

[3] Executive Order 14154 of January 20, 2025, "Unleashing American Energy," 90 *Federal Register* 8353, January 29, 2025; Catrin Einhorn, "Trump Killed a Major Report on Nature. They're Trying to Publish It Anyway," *New York Times*, February 10, 2025, https://www.nytimes.com/2025/02/10/climate/nature-assessment-trump.html; Lynda V. Mapes, "WA Scientists Plan to Publish Report on Nature That Trump Canceled," *Seattle Times*, February 17, 2025, https://www.seattletimes.com/seattle-news/climate-lab/wa-scientists-plan-to-publish-report-on-nature-that-trump-canceled/.

[4] U.S. Global Change Research Program (USGCRP), "About USGCRP," https://www.globalchange.gov/about-us, archived April 17, 2025, at https://perma.cc/NC9W-BCZW.

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supporting USGCRP was canceled.[5] In addition, federal staff previously involved in the program have reportedly been dismissed or are no longer working on USGCRP activities.[6]

Members of recent Congresses have also proposed both restricting USGCRP's funding and expanding its scope. As the Trump Administration looks to alter USGCRP and other activities related to climate change, an issue for the 119th Congress may be whether—and if so, how—to alter congressional direction and funding for USGCRP and its activities.

This report provides an overview of USGCRP, beginning with background information, followed by information about its member agencies and interagency groups, scientific assessments, and international activities. This report's description of activities is largely based on USGCRP's structure and activities as they existed prior to the Administration undertaking its review of USGCRP operations and structure. The report notes staffing and organizational changes reported in 2025.[7] The report concludes with considerations for Congress.

History, Functions, and Structure

USGCRP originated from interagency planning activities under the Reagan Administration.[8] USGCRP was established by Congress in 1990 by the GCRA (P.L. 101-606) in order to "assist the Nation and the world to understand, assess, predict, and respond to human-induced and natural processes of global change."

What Is *Global Change*?

Global change refers to large-scale shifts in Earth's environment that can affect ecosystems, resources, and human well-being. As defined by the Global Change Research Act of 1990 (GCRA; P.L. 101-606), *global change* means global environmental changes in climate, land productivity, oceans and other water resources, atmospheric chemistry, and ecological systems that may alter Earth's capacity to sustain life.

These changes are driven both by human activities—such as fossil fuel combustion, land-use change (agriculture, deforestation, urbanization), and industrial pollution—and natural processes, including volcanic eruptions and other geological events.

Global change research, as defined in the GCRA, includes the study, monitoring, assessment, prediction, and management of information related to the physical, chemical, and biological processes that regulate the Earth system, the changes occurring within it, and the influence of human activities.

[5] This news was first reported by *Politico* and subsequently confirmed and reported by other news organizations including *Science*, *Nature*, and *The Washington Post*. See Zack Colman, "Trump Moves to Hobble Major U.S. Climate Change Study," *Politico*, April 9, 2025, https://www.politico.com/news/2025/04/09/trump-moves-to-hobble-major-climate-study-00280405; Paul Voosen, "Trump Administration Fires Staff for Flagship U.S. Climate Assessment," *Science Insider*, April 14, 2025, https://doi.org/10.1126/science.z7pt5eu; Jeff Tollefson, "US Pulls Back from Gold-Standard Scientific Climate Panel," *Nature*, vol. 639, no. 17 (2025); Scott Dance and Sarah Kaplan, "Trump's New Reason for Canceling Grants: 'Climate Anxiety,'" *Washington Post*, April 10, 2025, https://www.washingtonpost.com/climate-environment/2025/04/10/trump-princeton-funding-cuts-climate-anxiety/.

[6] A number of news reports indicated that federal staff previously involved in USGCRP activities had been dismissed or were no longer working on the program. For examples, see Paul Voosen, "Trump Administration Fires Staff for Flagship U.S. Climate Assessment," *Science Insider*, April 14, 2025, https://doi.org/10.1126/science.z7pt5eu; Paul Voosen, "NASA Cuts Off International Climate Science Support," *Science Insider*, February 24, 2025, https://doi.org/10.1126/science.zdvyfcx.

[7] Paul Voosen, "Trump Administration Fires Staff for Flagship U.S. Climate Assessment," *Science Insider*, April 14, 2025, https://doi.org/10.1126/science.z7pt5eu; Paul Voosen, "NASA Cuts Off International Climate Science Support," *Science Insider*, February 24, 2025, https://doi.org/10.1126/science.zdvyfcx.

[8] National Academies of Sciences, Engineering, and Medicine (NASEM), *Accomplishments of the U.S. Global Change Research Program*, 2017, https://doi.org/10.17226/24670.

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Pursuant to statute, USGCRP has four major sets of responsibilities under the GCRA:

1. coordinating global change research across the federal government,[9]
2. developing and distributing mandated products,[10]
3. providing scientific information to inform policy decisions,[11] and
4. facilitating international research coordination.[12]

USGCRP coordinates global change research across federal agencies, including through its interagency groups.[13] USGCRP's mandated products include (1) a strategic research plan released every 10 years with updates every 3 years,[14] (2) a scientific assessment that synthesizes the findings of the program and analyzes the effects of global change at least every 4 years,[15] and (3) an annual report.[16] These mandated products are designed to provide scientific information that is useful to policymakers. USGCRP's annual report—*Our Changing Planet*—provides updates to Congress on its activities and budget and documents programmatic achievements.[17] In addition, USGCRP supports the development of datasets and tools to provide decisionmakers with accessible and policy-relevant scientific information.[18]

USGCRP supports international collaboration on global change research by engaging with global scientific organizations and research initiatives. USGCRP supports U.S. participation in international scientific assessments. This has included assessments by the World Meteorological Organization (WMO) and the United Nations Environment Programme (UNEP), such as ozone depletion assessments and the IPCC's periodic climate change assessment reports.[19]

USGCRP operates under the National Science and Technology Council (NSTC) and is overseen by the White House Office of Science and Technology Policy (OSTP).[20] The NSTC's

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[9] 15 U.S.C. §2932(e)(2).

[10] 15 U.S.C. §2934(a); 15 U.S.C. §2936; 15 U.S.C. §2937.

[11] 15 U.S.C. §2932(e)(6).

[12] 15 U.S.C. §2932(e)(5).

[13] USGCRP, *Our Changing Planet: The U.S. Global Change Research Program for Fiscal Year 2025*, 2024 (hereinafter USGCRP, *Annual Report*, 2024).

[14] 15 U.S.C. §2934(a); USGCRP, *The U.S. Global Change Research Program 2022-2031 Strategic Plan*, 2022 (hereinafter USGCRP, *Research Strategic Plan 2022-2031*, 2022).

[15] 15 U.S.C. §2936.

[16] 15 U.S.C. §2937.

[17] Annual reports are available at USGCRP, "Reports Library," https://globalchange.govarchive.us/reports?topic%5B122%5D=122/.

[18] For example, USGCRP supports the U.S. Climate Resilience Toolkit, which provides data, maps, and case studies to help communities assess and prepare for climate-related risks (available at https://toolkit.climate.gov/).

[19] Intergovernmental Panel on Climate Change (IPCC), "Preparing Reports," https://www.ipcc.ch/about/preparingreports/, archived March 26, 2025, at https://perma.cc/3U7F-BR5Y. "Created in 1988 by the World Meteorological Organization (WMO) and the United Nations Environment Programme (UNEP)," the IPCC "is the United Nations body for assessing the science related to climate change." IPCC, "About the IPCC," https://www.ipcc.ch/about/.

[20] USGCRP was originally coordinated by the Committee on Earth and Environmental Sciences (CEES), as stipulated in the Global Change Research Act (GCRA). President Clinton disbanded the CEES as part of a larger science and technology reorganization effort and reconstituted these research efforts as the U.S. Global Change Research Program under a subcommittee of the National Science and Technology Council (NSTC). For more information on the administrative history of USGCRP, see National Academies of Sciences, Engineering, and Medicine, *Accomplishments of the U.S. Global Change Research Program*, 2017, p. 5, https://doi.org/10.17226/24670. For more information on the NSTC, see CRS Report R47410, *The Office of Science and Technology Policy (OSTP): Overview and Issues for Congress*, by Emily G. Blevins.

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Subcommittee on Global Change Research (SGCR) and Subcommittee on Climate Services lead USGCRP's activities and coordinate interagency efforts through the USGCRP National Coordination Office (NCO) and, according to a previous website of USGCRP, 17 interagency groups.[21] Representatives from each participating department and agency constitute USGCRP. In addition, the Executive Office of the President and other related entities have designated liaisons that participate in the SGCR.[22] The National Academies of Sciences, Engineering, and Medicine's (NASEM's) Committee to Advise USGCRP provides ongoing guidance, including reviewing draft strategic plans.[23]

According to a 2022 Government Accountability Office (GAO) report, USGCRP's NCO provides operational support and technical expertise to the program by planning, coordinating, and assisting USGCRP activities; in FY2020, the NCO's budget was $8.1 million.[24] GAO also reported that, as of August 2022, USGCRP had three employees on detail from participating agencies within its NCO and 25 contractor staff. GAO further reported that the USGCRP NCO was managed by a consultancy contract with the National Aeronautics and Space Administration (NASA).[25] As stated earlier in this report, the contract was reportedly canceled in April 2025.[26]

Member Agencies and Departments

USGCRP coordinates global change research across 15 federal agencies and departments that either conduct global change research or rely on it to carry out their missions.[27] This research spans multiple disciplines and includes Earth observations through long-term continuous data collection, studies of past changes in the Earth system, quantitative modeling to predict future conditions, and interdisciplinary research examining interactions among physical, chemical, biological, and social processes related to global change.

Federal agencies and departments engage in different aspects of this research depending on their statutory mandates, missions, and areas of expertise. Each agency has distinct authorities, expertise, and research networks, as well as separate program and budget structures. USGCRP has no authority over individual agency missions or budgets (see "Budget Information"). USGCRP provides a framework to coordinate research activities—to ensure they are complementary, reduce duplication, and collectively advance understanding of global change.

[21] USGCRP, "Interagency Groups," https://www.globalchange.gov/our-work/interagency-groups, archived March 24, 2025, at https://perma.cc/X3JJ-LEAS.

[22] Other participants include representatives from the Office of Science and Technology Policy (OSTP), Council on Environmental Quality (CEQ), Office of Management and Budget (OMB), Climate Change Technology Program (CCTP), and the Office of the Federal Coordinator for Meteorology (OFCM).

[23] NASEM, *Review of the U.S. Global Change Research Program's Draft Decadal Strategic Plan, 2022-2031*, 2022, https://doi.org/10.17226/26608.

[24] U.S. Government Accountability Office (GAO), *Federal Research and Development: Funding Has Grown*, GAO-23-105396, December 2022, p. 49 (hereinafter GAO, *Federal Research and Development: Funding Has Grown*, 2022).

[25] GAO, *Federal Research and Development: Funding Has Grown*, 2022. The contract was with the consultant ICF Incorporated LLC, also referred to as ICF International. While the contract is not publicly available, some additional information can be found in the National Aeronautics and Space Administration's (NASA's) press release about the contract award. See NASA, "NASA Awards Global Change Research Support Services Contract," press release, April 8, 2021, https://www.nasa.gov/news-release/nasa-awards-global-change-research-support-services-contract/, archived April 17, 2025, at https://perma.cc/GG9L-URD9.

[26] Paul Voosen, "Trump Administration Fires Staff for Flagship U.S. Climate Assessment," *Science Insider*, April 14, 2025, https://doi.org/10.1126/science.z7pt5eu.

[27] USGCRP, *Annual Report*, 2024.

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Participating agencies and departments have included the

- Department of Agriculture;
- Department of Commerce;[28]
- Department of Defense;
- Department of Energy;
- Department of Health and Human Services;
- Department of Homeland Security;
- Department of Housing and Urban Development;
- Department of the Interior;
- Department of State;
- Department of Transportation;
- Environmental Protection Agency;
- National Aeronautics and Space Administration;
- National Science Foundation;
- Smithsonian Institution; and
- U.S. Agency for International Development.

Budget Information

In the USGCRP annual report to Congress, USGCRP reports budget data on activities supporting USGCRP for many of its member agencies and departments—that is, the budget crosscut shows the funding self-identified by agencies and departments as their contributions to USGCRP.

Table 1 presents selected fiscal year information, by agency, drawn from the publicly available budget crosscuts (which are available through FY2023), adjusted for inflation. The budget crosscut does not include all agency investments directly relevant and necessary for USGCRP to carry out its objectives. For example, costs related to observing networks such as satellite systems—which provide important data for observing global change—are not included in the budget crosscut. In addition, not all agencies report costs. For example, the Department of Defense has not recently reported funding through the USGCRP budget crosscut. Each agency develops and implements its own activities as part of its contribution to USGCRP, with funds appropriated directly to the agency for those activities. These activities may or may not be explicitly identified as USGCRP-related in agency budget justifications or other publicly available materials. USGCRP does not have authority over agency budgets and does not control how funds are allocated.

[28] The National Oceanic and Atmospheric Administration (NOAA) and the National Institute of Standards and Technology (NIST) have comprised Department of Commerce's participation in USGCRP.

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Table 1. Crosscut by Agency for Expenditures in Support of USGCRP, Selected Years, Inflation-Adjusted 2023 Dollars

Funding amounts are shown in millions of dollars and are rounded to the nearest million

	FY 1990	FY 2000	FY 2010	FY 2020	FY 2021	FY 2022	FY 2023
National Aeronautics and Space Administration	763	1,589	1,350	1,597	1,727	1,815	1,774
National Science Foundation	86	255	384	267	709	764	836
U.S. Agency for International Development	—	—	43	—	—	—	—
U.S. Department of Commerce	28	91	434	333	478	501	588
U.S. Department of Agriculture	33	72	133	121	127	145	198
U.S. Department of Energy	78	154	205	278	328	367	380
U.S. Department of Health and Human Services	—	62	5	11	31	30	187
U.S. Environmental Protection Agency	20	28	25	20	21	20	21
U.S. Department of the Interior	20	31	76	41	222	241	252
U.S. Department of Transportation	—	—	5	0	1	2	2
Smithsonian Institution	—	9	8	9	9	8	9
Total	**1,028**	**2,291**	**2,668**	**2,677**	**3,653**	**3,893**	**4,247**

Source: Prepared by CRS from U.S. Global Change Research Program (USGCRP) annual report (*Our Changing Planet*) data. Annual reports are available at USGCRP, "Reports Library," https://globalchange.govarchive.us/reports?topic%5B122%5D=122. Inflation adjustment calculated using Bureau of Economic Analysis, *National Data: National Income and Product Accounts*, "Table 5.9.4. Price Indexes for Gross Government Fixed Investment by Type," line 4, September 27, 2024, https://apps.bea.gov/iTable/?reqid=19&step=2&isuri=1&categories=survey.

Interagency Groups

Interagency groups have coordinated and supported implementation of global change research activities within and across USGCRP agencies and departments. USGCRP's interagency groups have historically been composed of representatives from federal agencies and departments responsible for activities in each area.

USGCRP has convened 17 interagency groups. It is uncertain if these working groups will continue to convene under the Trump Administration. USGCRP has convened working groups focused on Earth system processes, such as carbon and water cycles.[29] Other working groups have focused on social sciences and public health.[30] A number of working groups have address adaptation and resilience, including assessing risks to ecosystems, infrastructure, coastal and urban areas, and national security.[31] Additional working groups specialized in data collection,

[29] These include the Carbon Cycle Interagency Working Group (CCIWG) and the Integrated Water Cycle Group (IWCG).

[30] These include the Social Sciences Coordinating Committee (SSCC) and the Interagency Crosscutting Group on Climate Change and Human Health (CCHHG).

[31] These include the Coasts Interagency Group (CoastsIG), Interagency Task Force on Sea Level Change (TF-SLC), Urban Interagency Group (UrbanIG), Working Group on National Security (WGNS), and Federal Adaptation and Resilience Group (FARG).

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climate modeling, and decision-support tools.[32] USGCRP also had working groups dedicated to public engagement and education, scientific assessments, and international coordination.[33]

Scientific Assessments

According to the GCRA, the purpose of USGCRP scientific assessments is to integrate, evaluate, and interpret USGCRP findings; discuss the scientific uncertainties associated with such findings; analyze the effects of global change; and analyze current trends in global change.

USGCRP periodically produces the NCA pursuant to statute; it also initiated, in 2022, a new periodic assessment—the National Nature Assessment (NNA)—pursuant to an executive order that was later revoked in 2025.[34] These assessments are discussed below.

National Climate Assessment

The GCRA requires USGCRP to develop an assessment of global change "not less frequently than every four years."[35] In response to this mandate, USGCRP has periodically produced an assessment titled the National Climate Assessment; these NCAs have synthesized the state of climate science and climate-related risks and impacts across each U.S. region and across major sectors of the economy. The NCA does not direct federal agencies to take specific actions; rather, it provides scientific information that agencies, policymakers, and stakeholders may use to support decisions such as those related to infrastructure resilience, disaster preparedness, economic risk assessment, and environmental planning.

To date, USGCRP has released five NCAs:

1. First National Climate Assessment (NCA1; 2000);[36]
2. Second National Climate Assessment (NCA2; 2009);[37]
3. Third National Climate Assessment (NCA3; 2014);[38]

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[32] These include the Integrated Observations Interagency Working Group (ObsIWG), Greenhouse Gas Measurement and Monitoring Interagency Working Group (GHG IWG), Interagency Group on Integrative Modeling (IGIM), Indicators Interagency Working Group (IndIWG), and Climate Services Technical Working Group (CS-TWG).

[33] These include the Climate Engagement and Capacity-Building Interagency Group (CEC), Sustained Assessment Working Group (SAWG), and International Activities Interagency Working Group (IAIWG).

[34] USGCRP has developed a number of other scientific assessments, including the first and second *State of the Carbon Cycle* reports, as well as reports focused on climate change and food and on climate change and human health. A. W. King et al., eds., *First State of the Carbon Cycle Report*, U.S. Climate Change Science Program and the Subcommittee on Global Change Research, 2007; N. Cavallaro et al., eds., *Second State of the Carbon Cycle Report*, USGCRP, 2018; A. J. Crimmins et al., eds., *The Impacts of Climate Change on Human Health in the United States: A Scientific Assessment*, USGCRP, 2016; M. E. Brown et al., *Climate Change, Global Food Security, and the U.S. Food System*, USGCRP, 2015.

[35] The GCRA specifies that each National Climate Assessment (NCA) must assess the potential effects of global change on a range of sectors and activities, including the natural environment, agriculture, energy, land and water resources, transportation, human health, social systems, and biodiversity. Each assessment must consider observed and projected trends, evaluate scientific advancements, and analyze climate-related risks over both near-term (25-year) and long-term (100-year) time frames.

[36] National Assessment Synthesis Team, *Climate Change Impacts on the United States: The Potential Consequences of Climate Variability and Change*, USGCRP, 2001.

[37] Thomas R. Karl et al., eds., *Global Climate Change Impacts in the United States*, USGCRP, 2009.

[38] Jerry M. Melillo et al., eds., *Climate Change Impacts in the United States: The Third National Climate Assessment*, USGCRP, 2014.

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4. Fourth National Climate Assessment (NCA4; 2017, 2018);[39] and
5. Fifth National Climate Assessment (NCA5; 2023).[40]

The NCAs have been written by hundreds of experts, including scientists working in federal government, academia, and the private sector. Each NCA has undergone multiple rounds of expert and governmental review, including evaluation by federal agencies, external experts, the public, and a NASEM review committee.[41]

According to USGCRP in 2023, NCA5 was the most comprehensive analysis of climate change in the United States.[42] In 2024, USGCRP began developing the Sixth National Climate Assessment (NCA6).[43] To comply with the requirement to produce an assessment every four years, the deadline to submit NCA6 to Congress is 2027.[44] In early 2025, under the second Trump Administration, work on NCA6 reportedly stopped and the report's authors were reportedly dismissed.[45]

National Nature Assessment

In 2022, the Biden Administration issued E.O. 14072, "Strengthening the Nation's Forests, Communities, and Local Economies," directing USGCRP to provide a comprehensive evaluation of the condition of nature in the United States.[46] In response, USGCRP initiated the First National Nature Assessment (NNA1) and defined its scope as follows:[47]

> The scope of NNA1 is to assess the status, observed trends, and future projections of America's lands, waters, wildlife, biodiversity, and ecosystems and the benefits they provide, including connections to the economy, public health, equity, climate mitigation and adaptation, and national security.

[39] The Fourth National Climate Assessment was published in two volumes, covering climate science (Vol. I, 2017) and climate impacts, risks, and adaptation strategies (Vol. II, 2018). D. J. Wuebbles et al., eds., *Climate Science Special Report: Fourth National Climate Assessment, Volume I*, USGCRP, 2017; D. R. Reidmiller et al., eds., *Impacts, Risks, and Adaptation in the United States: Fourth National Climate Assessment, Volume II*, USGCRP, 2018.

[40] C. W. Avery et al., eds., *Fifth National Climate Assessment*, USGCRP, 2023.

[41] NASEM, *Review of the Draft Fifth National Climate Assessment*, 2023, https://doi.org/10.17226/26757.

[42] USGCRP, "U.S. Global Change Research Program Releases Fifth National Climate Assessment," press release, November 14, 2023.

[43] USGCRP, *Annual Report*, 2024.

[44] 15 U.S.C. §2936 requires that a report assessing global change be submitted to the President and Congress "not less frequently than every four years." Following the first National Climate Assessment (2000), the second assessment was not released until 2009. In 2005, a U.S. District Court ruled that the delay violated the statute and ordered the Administration to comply. See *Center for Biological Diversity v. Brennan*, 571 F. Supp. 2d 1105 (N.D. Cal. 2007).

[45] Paul Voosen, "Trump Administration Fires Staff for Flagship U.S. Climate Assessment," *Science Insider*, April 14, 2025, https://doi.org/10.1126/science.z7pt5eu; Paul Voosen, "NASA Cuts Off International Climate Science Support," *Science Insider*, February 24, 2025, https://doi.org/10.1126/science.zdvyfcx; Brad Plumer and Rebecca Dzombak, "All Authors Working on Flagship U.S. Climate Report Are Dismissed," *New York Times*, April 28, 2025, https://www.nytimes.com/2025/04/28/climate/national-climate-assessment-authors-dismissed.html.

[46] Executive Order 14072, "Strengthening the Nation's Forests, Communities, and Local Economies," 87 *Federal Register* 24851, April 22, 2022.

[47] OSTP, "Framing the National Nature Assessment," 87 *Federal Register* 65622, October 31, 2022. Department of the Interior (DOI), "Request for Public Nominations for Authors and Scientific/Technical Inputs for the First National Nature Assessment," 88 *Federal Register* 80747, November 20, 2023.

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A draft outline was released for public comment in 2024.[48] USGCRP anticipated releasing a draft for public comment in early 2025 and releasing the final report in 2026.[49]

In 2025, the Trump Administration issued E.O. 14154, "Unleashing American Energy," which revoked a number of executive orders from the Biden Administration, including E.O. 14072.[50] USGCRP's efforts to develop NNA1 were reportedly discontinued.[51]

International Coordination and Research

Under the GCRA, USGCRP is charged with coordinating global change research activities with other nations and international organizations. USGCRP, its interagency groups, and member agencies have participated in a variety of international activities, including international scientific assessments and collaborative research efforts, as well as meetings and conferences.

USGCRP, in coordination with the U.S. Department of State, has provided U.S. representation at international meetings and conferences on global change research and supported U.S. scientists' participation in international scientific assessments. For example, USGCRP has managed the nomination process for U.S. scientists, served as the point of contact for communication with international scientific bodies, and coordinated interagency review and input. These international assessments have included those conducted by the UNEP, WMO, IPCC, and others. The findings from these assessments provide the scientific basis for international conventions and protocols, including the Montreal Protocol on Substances That Deplete the Ozone Layer and the United Nations Framework Convention on Climate Change.[52]

USGCRP has historically collaborated with international and regional research initiatives and scientific organizations, and supported global monitoring networks. USGCRP has contributed to the development and maintenance of global monitoring systems that track environmental change, and facilitates data sharing and coordinates research on global change issues.[53]

In February 2025, the Trump Administration reportedly restricted U.S. scientists' participation in an international planning meeting to develop the IPCC's Seventh Assessment Report (AR7).[54] At the time, the United States was serving as a co-chair of IPCC Working Group III, which focuses on climate mitigation. NASA's chief scientist, who had been designated to serve as co-chair of that IPCC working group, was removed from the role.[55]

In the absence of federal coordination, a newly established nongovernmental organization—the U.S. Academic Alliance for the IPCC (USAA), hosted by the American Geophysical Union (AGU)—has taken steps to maintain U.S. engagement in the assessment process. In April 2025,

[48] DOI, "Draft Outline for the First National Nature Assessment," 89 *Federal Register* 76867, September 19, 2024; USGCRP, *Annual Report*, 2024.

[49] USGCRP, *Annual Report*, 2024, p. 65.

[50] Executive Order 14154 of January 20, 2025, "Unleashing American Energy," 90 *Federal Register* 8353, January 29, 2025.

[51] Catrin Einhorn, "Trump Killed a Major Report on Nature. They're Trying to Publish It Anyway," *New York Times*, February 10, 2025, https://www.nytimes.com/2025/02/10/climate/nature-assessment-trump.html.

[52] USGCRP, *Research Strategic Plan 2022-2031*, 2022.

[53] For example, USGCRP participates in the World Climate Research Programme (WCRP), AmeriGEO, and the Inter-American Institute for Global Change Research (IAI). USGCRP, *Annual Report*, 2024.

[54] Jeff Tollefson, "US Pulls Back from Gold-Standard Scientific Climate Panel," *Nature*, vol. 639, no. 17 (2025).

[55] Jeff Tollefson, "US Pulls Back from Gold-Standard Scientific Climate Panel," *Nature*, vol. 639, no. 17 (2025).

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the USAA issued a call for nominations of U.S. experts, authors, and review editors to contribute to AR7.[56]

Considerations for Congress

USGCRP began as a presidential initiative under the Reagan Administration in 1989 and was established by Congress in 1990 under the GCRA to develop a comprehensive and integrated U.S. research program to assist both the nation and the world in understanding, assessing, predicting, and responding to global environmental change. The Trump Administration is reviewing executive branch activities related to climate change, including the structure and operations of USGCRP, and has initiated changes affecting the program. USGCRP-related issues for the 119th Congress may include whether—and if so, how—to alter congressional direction and funding for USGCRP and its activities, whether to reverse or codify in statute actions that may be taken by the Trump Administration, and whether to conduct oversight and investigation to inform USGCRP's actions.

Decisions related to altering USGCRP encompass not only the funding and scientific resources dedicated to supporting USGCRP activities and the extent to which those funds and resources may or may not be diverted to other research endeavors, but also the potential implications of changes for the type, reliability, accessibility, coordination, and transparency of global change data and research. These data and research changes may have implications for global change scientific assessments and the policy and investment decisions the assessments inform.

Members of Congress may consider whether to support USGCRP continuing its activities under the GCRA. Alternatively, Members may consider how USGCRP's role and structure could change, or how the types of scientific activities and information USGCRP supports could change. USGCRP has aimed to provide publicly accessible scientific information on global change, such as assessments, datasets, and tools, that inform domestic and international policymakers, including by addressing global-change-related scientific confidence, uncertainty, and research gaps. Members may consider whether it serves the American public for the federal government to continue performing this role and, if so, whether USGCRP should remain the primary entity coordinating these efforts.

In past Congresses, Members have expressed a range of views. Some Members have proposed restricting the use of federal funding for USGCRP.[57] Other Members have sought to expand its scope, including by directing USGCRP to establish new working groups or undertake additional activities, such as initiatives related to extreme weather and resilience.[58]

USGCRP has periodically produced the NCA, synthesizing scientific understanding of climate trends and sectoral and regional impacts, as well as produced usable information for policymakers to formulate effective strategies related to global change. The first Trump Administration was critical of USGCRP activities, including the NCAs.[59] Under the Biden Administration, USGCRP

[56] American Geophysical Union, "New U.S. Academic Alliance for the IPCC Opens Critical Nomination Access," press release, 2025, https://news.agu.org/press-release/usaa-ipcc-opens-nominations-seventh-assessment/.

[57] For example, see H.Amdt. 1163 (118th Congress), H.Amdt. 597 (118th Congress), H.Amdt. 758 (113th Congress), and H.Amdt. 671 (113th Congress).

[58] For example, see H.R. 2872 (117th Congress), S. 1420 (117th Congress), H.R. 2748 (116th Congress), S. 1482 (116th Congress), H.R. 2760 (117th Congress), S. 1282 (117th Congress), H.R. 5994 (116th Congress), and S. 3349 (116th Congress).

[59] White House, "Press Briefing by Press Secretary Sarah Sanders, Director of the NEC Larry Kudlow, and NSC Advisor John Bolton," press release, November 27, 2018, https://trumpwhitehouse.archives.gov/briefings-statements/ (continued...)

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completed NCA5 and initiated the development of NCA6. The second Trump Administration has reportedly canceled NASA's contract with consulting firm ICF International. This firm provided staff and services that supported USGCRP activities, including the development of the NCA6.[60] The authors working on NCA6 were dismissed, according to news reports.[61] It is uncertain if the second Trump Administration will continue efforts to produce NCA6—relying on authors other than those that were reportedly dismissed—or whether it will pursue an alternative approach to comply with the GCRA-mandated assessment. Members may consider supporting the completion of NCA6, directing USGCRP to halt the assessment, or having USGCRP focus on certain aspects of global change, among other actions.

The reported cancellation of NNA1 in 2025 raises considerations for Congress regarding the development and dissemination of this scientific assessment. USGCRP initiated NNA1 in 2022 and was anticipating releasing the first draft in early 2025.[62] Congress may seek to clarify whether or not USGCRP should publicly release this scientific assessment. Alternatively, Congress might redirect efforts toward other priorities. Some researchers involved in NNA1 have expressed interest in publishing their findings independently through academic journals or other nongovernmental platforms. While this approach could make this information publicly available, it may lack the authoritativeness of a government report.

USGCRP facilitates U.S. participation in international scientific global change research efforts. For example, USGCRP, together with the U.S. Department of State, has facilitated U.S. participation in developing scientific assessments conducted by the IPCC. According to USGCRP in 2022, the U.S. government played a pivotal role in establishing the IPCC, and U.S. experts have contributed to every assessment.[63] The Trump Administration has reportedly restricted U.S. scientists' participation in the next IPCC assessment.[64] While recent actions by the Trump Administration have limited the participation of federal scientists in international assessments, these restrictions do not apply to scientists affiliated with academic institutions or nongovernmental organizations. The nongovernmental organization U.S. Academic Alliance for the IPCC issued a call for nominations for U.S. scientists to participate in the IPCC's Seventh Assessment Report.

Members may consider the role of USGCRP in facilitating U.S. participation in IPCC assessments and whether the federal government should continue to play a prominent role in international scientific assessments. Historically, federal participation has meant that U.S. scientific perspectives and priorities across the federal government have often been integrated into international global climate assessments, which in turn inform domestic policy and international negotiations. A shift to nonfederal participation—for example, through academic institutions or nongovernmental organizations—could maintain some level of U.S. scientific contributions but may reduce the ability of the United States to (1) coordinate input from other

press-briefing-press-secretary-sarah-sanders-director-nec-larry-kudlow-nsc-advisor-john-bolton-112818/; Scott Waldman, "Trump Official Who Tried to Downplay Major Climate Report Now Will Oversee It," *Politico E&E News*, March 3, 2025.

[60] Paul Voosen, "Trump Administration Fires Staff for Flagship U.S. Climate Assessment," *Science Insider*, April 14, 2025, https://doi.org/10.1126/science.z7pt5eu.

[61] Brad Plumer and Rebecca Dzombak, "All Authors Working on Flagship U.S. Climate Report Are Dismissed," *New York Times*, April 28, 2025, https://www.nytimes.com/2025/04/28/climate/national-climate-assessment-authors-dismissed.html.

[62] Catrin Einhorn, "Trump Killed a Major Report on Nature. They're Trying to Publish It Anyway," *New York Times*, February 10, 2025.

[63] USGCRP, *Research Strategic Plan 2022-2031*, 2022, p. 29.

[64] Jeff Tollefson, "US Pulls Back from Gold-Standard Scientific Climate Panel," *Nature*, vol. 639, no. 17 (2025).

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participants and (2) promote national scientific priorities in international assessment processes. Congress may weigh these and other considerations when deliberating on the extent of U.S. involvement in future international scientific assessments, and the scope and priorities of USGCRP's activities—and the potential impacts on efforts to understand and address climate change.

Author Information

Kathryn G. Kynett
Analyst in Environmental Policy

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From: John Christy <climateman60@gmail.com>
Sent: Monday, August 4, 2025 10:49 AM
To: Steven Koonin
Cc: ross.mckitrick@uoguelph.ca; curry.judith@yahoo.com; Roy Spencer; Travis Fisher; Charles Park; Joshua Loucks; Seth Cohen; Audrey Barrios
Subject: Re: Responses to DOE reviewers

Who will be the curator of the Response to DoE reviewers? Judy?

If I have a few suggestions, I'd rather just send those to the curator rather than reply with the whole document.

John C.

On Sun, Aug 3, 2025 at 11:48 AM Steven Koonin <steven.koonin@gmail.com> wrote:

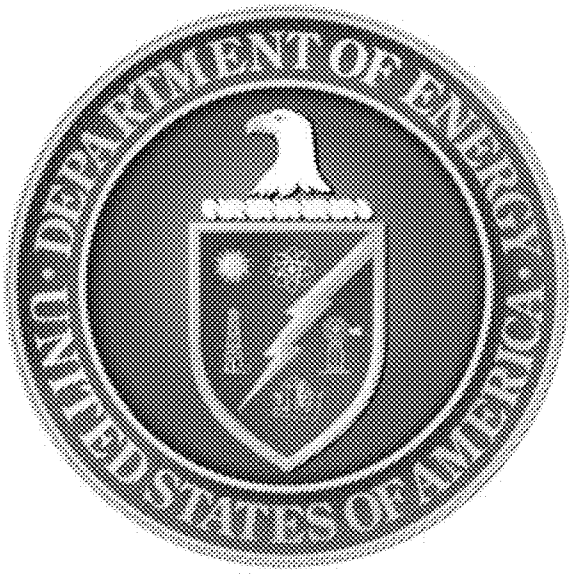
> I've been absent from this morning's exchanges as I've been reading through our responses to the various DOE reviewers. My light edits are in the attached zip file, together with the version of CWG25 that was sent out for review (perhaps we should include that in whatever is posted, although it might be revealing too much of how the sausage was made; thoughts?)
>
> Now turning to read RPjr's post.
>
> Steve Koonin

From: Steven Koonin [steven.koonin@gmail.com]
Sent: 8/3/2025 4:48:39 PM
To: ross.mckitrick@uoguelph.ca; curry.judith@yahoo.com; 'John Christy' [climateman60@gmail.com]; 'Roy Spencer' [roy.spencer@nsstc.uah.edu]
CC: 'Travis Fisher' [travis.fisher@hq.doe.gov]; 'Charles Park' [charles.park@hq.doe.gov]; 'Joshua Loucks' [Joshua.Loucks@hq.doe.gov]; 'Seth Cohen' [seth.cohen@hq.doe.gov]; 'Audrey Barrios' [audrey.barrios@hq.doe.gov]
Subject: Responses to DOE reviewers
Attachments: DOE review responses SEK.zip

I've been absent from this morning's exchanges as I've been reading through our responses to the various DOE reviewers. My light edits are in the attached zip file, together with the version of CWG25 that was sent out for review (perhaps we should include that in whatever is posted, although it might be revealing too much of how the sausage was made; thoughts?)

Now turning to read RPjr's post.

Steve Koonin



Impacts of Carbon Dioxide Emissions on the U.S. Climate

Climate Working Group
United States Department of Energy
July 15, 2025

Impacts of Carbon Dioxide Emissions on the U.S. Climate

Report to U.S. Energy Secretary Christopher Wright

July 15, 2025

Climate Working Group:

John Christy, Ph.D.

Judith Curry, Ph.D.

Steven Koonin, Ph.D.

Ross McKitrick, Ph.D.

Roy Spencer, Ph.D.

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Table of Contents

SECRETARY'S FOREWORD VII
EXECUTIVE SUMMARY VIII
PREFACE IX
PART I: DIRECT HUMAN INFLUENCE ON ECOSYSTEMS AND THE CLIMATE 1
1 CARBON DIOXIDE AS A POLLUTANT 2
2 DIRECT IMPACTS OF CO_2 ON THE ENVIRONMENT 3
2.1 CO_2 AND GLOBAL GREENING 3
2.1.1 Measurement of global greening 3
2.1.2 Photosynthesis and CO_2 levels 4
2.1.3 Rising CO_2 and crop water use efficiency 6
2.1.4 CO_2 fertilization benefits in IPCC Reports 7
2.2 THE ALKALINE OCEANS 7
2.2.1 Changing pH 7
2.2.2 Coral reef changes 8
3 HUMAN INFLUENCES ON THE CLIMATE 12
3.1 COMPONENTS OF RADIATIVE FORCING AND THEIR HISTORY 12
3.1.1 Historical radiative forcing 12
3.1.2 Change in atmospheric CO_2 since 1958 14
3.2 FUTURE EMISSION SCENARIOS AND THE CARBON CYCLE 15
3.2.1 Emission scenarios 15
3.2.2 The carbon cycle relating emissions and concentrations 18
3.3 URBANIZATION INFLUENCE ON TEMPERATURE TRENDS 21
PART II: CLIMATE RESPONSE TO CO_2 EMISSIONS 25
4 CLIMATE SENSITIVITY TO CO_2 FORCING 26
4.1 INTRODUCTION 26
4.2 MODEL-BASED ESTIMATES OF CLIMATE SENSITIVITY 27
4.3 DATA-DRIVEN ESTIMATES OF CLIMATE SENSITIVITY 28
4.4 TRANSIENT CLIMATE RESPONSE 30
5 MODELS VERSUS OBSERVATIONS IN THE RECENT PAST 32
5.1 INTRODUCTION 32
5.2 SURFACE WARMING 34
5.3 TROPOSPHERIC WARMING 35
5.4 VERTICAL TEMPERATURE PROFILE MISMATCH 37

DOJ_00000526

5.5 STRATOSPHERIC COOLING 39
5.6 SNOW COVER MISMATCH 40
5.7 HEMISPHERIC SYMMETRY OF THE PLANETARY ALBEDO 42
5.8 U.S. CORN BELT 43
6 EXTREME WEATHER 47
6.1 INTRODUCTION 47
6.2 HURRICANES AND TROPICAL CYCLONES 49
6.3 TEMPERATURE EXTREMES 53
6.3.1 Temperatures in the U.S. are becoming less extreme 54
6.3.2 Exceedances of a heat threshold 57
6.3.3 Heatwaves 58
6.4 EXTREME PRECIPITATION 60
6.5 TORNADOES 67
6.6 FLOODING 68
6.7 DROUGHTS 68
6.8 WILDFIRES 69
7 CHANGES IN SEA LEVEL 75
7.1 GLOBAL SEA LEVEL RISE 75
7.2 U.S. SEA LEVEL RISE 75
7.3 PROJECTED SEA LEVEL RISE 79
8 UNCERTAINTIES IN CLIMATE CHANGE ATTRIBUTION 82
8.1 INTRODUCTION 82
8.2 ATTRIBUTION METHODS 83
8.3 ATTRIBUTION OF GLOBAL WARMING 84
8.3.1 Natural climate variability 84
8.3.2 Optimal fingerprinting 88
8.3.3 Time series methods 89
8.4 DECLINING PLANETARY ALBEDO AND RECENT RECORD WARMTH 90
8.5 ATTRIBUTION OF CLIMATE IMPACT DRIVERS 92
8.6 EXTREME EVENT ATTRIBUTION (EEA) 95
8.6.1 Case study – 2021 Western North America heat wave 96
PART III: IMPACTS ON ECOSYSTEMS AND SOCIETY 103
9 CLIMATE CHANGE AND U.S. AGRICULTURE 104
9.1 ECONOMETRIC ANALYSES 104
9.2 FIELD STUDIES OF CO_2 ENRICHMENT 105

DOJ_00000527

9.3 CROP MODELING META-ANALYSES 107
9.4 CO_2 FERTILIZATION AND NUTRIENT LOSS 108
10 MANAGING RISKS OF EXTREME WEATHER 110
10.1 SOCIOECONOMIC CONTEXT 110
10.2 DATA CHALLENGES 111
10.3 MORTALITY FROM TEMPERATURE EXTREMES 111
10.3.1 Heat and cold risks 111
10.3.2 Mortality risks and energy costs 113
11 CLIMATE CHANGE, THE ECONOMY, AND THE SOCIAL COST OF CARBON 116
11.1 CLIMATE CHANGE AND ECONOMIC GROWTH 116
11.1.1 Overview 116
11.1.2 Empirical analysis of climate change and economic growth 119
11.2 MODELS OF THE SOCIAL COST OF CARBON 120
11.2.1 Estimating the SCC 121
11.2.2 Variations in the SCC 122
11.2.3 Evidence for low SCC 123
11.2.4 Tipping points 123
11.2.5 Are there alternatives? 125
12 GLOBAL CLIMATE IMPACTS OF U.S. EMISSIONS POLICIES 129
12.1 THE SCALE PROBLEM 129
12.2 CASE STUDY: U.S. MOTOR VEHICLE EMISSIONS 129
GLOSSARY 131
METADATA FOR FIGURES AND TABLES 135
ABOUT THE AUTHORS 139

DOJ_00000528

SECRETARY'S FOREWORD

Energy, Integrity, and the Power of Human Potential

Over my lifetime, I've had the privilege of working as an energy entrepreneur across a range of fields—nuclear, geothermal, natural gas, and more—and I now serve as Secretary of Energy under President Donald Trump. But above all, I'm a physical scientist who sees modern energy as nothing short of miraculous. It powers every aspect of modern life, drives every industry, and has made America an energy powerhouse with the ability to fuel global progress.

The rise of human flourishing over the past two centuries is a story worth celebrating. Yet we are told—relentlessly—that the very energy systems that enabled this progress now pose an existential threat. Hydrocarbon-based fuels, the argument goes, must be rapidly abandoned or else we risk planetary ruin.

That view demands scrutiny. That's why I commissioned this report: to encourage a more thoughtful and science-based conversation about climate change and energy. With my technical background, I've reviewed reports from the Intergovernmental Panel on Climate Change, the U.S. government's assessments, and the academic literature. I've also engaged with many climate scientists, including the authors of this report.

What I've found is that media coverage often distorts the science. Many people—even well-meaning ones—walk away with a view of climate change that is exaggerated or incomplete. To provide clarity, I asked a diverse team of independent experts to summarize the current state of climate science, with a focus on how it relates to the United States.

I didn't select these authors because we always agree—far from it. In fact, they may not always agree with each other. But I chose them for their rigor, honesty, and willingness to elevate the debate. I exerted no control over their conclusions. What you'll read are their words, drawn from the best available data and scientific assessments.

I've reviewed the report carefully and challenged its findings. I believe it faithfully represents the state of climate science today. Still, many readers may be surprised by its conclusions—which differ in important ways from the mainstream narrative. That's a sign of how far the public conversation has drifted from the science itself.

To correct course, we need open, respectful, and informed debate. That's why I'm inviting public comment on this report. Honest scrutiny and scientific transparency should be at the heart of our policymaking.

Climate change is real, and it deserves attention. But it is not the greatest threat facing humanity. That distinction belongs to global energy poverty. As someone who values data, I know that improving the human condition depends on expanding access to reliable, affordable energy. Climate change is a challenge—not a catastrophe. But misguided policies based on fear rather than facts could truly endanger human well-being.

We stand at the threshold of a new era of energy leadership. If we empower innovation rather than restrain it, America can lead the world in providing cleaner, more abundant energy—lifting billions out of poverty, strengthening our economy, and improving our environment along the way.

EXECUTIVE SUMMARY

This report reviews scientific certainties and uncertainties in how anthropogenic carbon dioxide (CO_2) emissions have affected, or will affect, the Nation's climate, extreme weather events, and selected metrics of societal well-being. Those emissions are increasing the concentration of CO_2 in the atmosphere through a complex and variable carbon cycle, where some portion of the additional CO_2 persists in the atmosphere for centuries.

Elevated concentrations of CO_2 directly enhance plant growth, globally "greening" the planet and increasing agricultural productivity. They also make the oceans less alkaline (lower the pH) by an amount within the range of natural variability. That is possibly detrimental to coral reefs, although the recent rebound of the Great Barrier Reef suggests otherwise.

Carbon dioxide also acts as a greenhouse gas, exerting a warming influence on climate and weather. Scenarios of future CO_2 emissions have tended to overestimate observed levels.

The world's several dozen detailed climate models offer little guidance on how the climate responds to elevated CO_2, with the average surface warming under a doubling of the CO_2 concentration ranging from 1.8°C to 5.7°C, a larger range than data driven estimates that suggest a response in the range 1.8°C to 2.7°C.

Detailed climate models generally run "hot" in their description of the climate of the past few decades - too much warming at the surface and too much amplification of warming in the lower- and mid-troposphere. They also produce too much stratospheric cooling, too much snow loss, and too much warming in the U.S. Corn Belt. The combination of overly sensitive models and extreme scenarios for future emissions has exaggerated projections of future warming.

Most extreme weather events do not show long-term trends. Claims of increased frequency or intensity of hurricanes, tornadoes, floods, and droughts are not supported by historical data. Additionally, forest management practices are often overlooked in assessing wildfire activity. Global sea level has risen approximately 8 inches since 1900, but there are significant regional variations in tide gauge data driven primarily by local land subsidence; U.S. tide gauge measurements in aggregate show no obvious acceleration in sea level rise beyond the historical average rate.

The attribution of particular climate changes or extreme weather events to human CO_2 emissions is challenged by natural climate variability, data limitations, and inherent model deficiencies. Moreover, solar activity's contribution to the late 20th century warming might be underestimated.

Both models and experience suggest that CO_2-induced warming might be less damaging economically than commonly believed, and excessively aggressive mitigation policies could prove more detrimental than beneficial. Social Cost of Carbon estimates, which attempt to quantify the economic damage of CO_2 emissions, are highly sensitive to their underlying assumptions and so provide limited independent information.

The report supports a more nuanced and evidence-based approach for informing climate policy. The risks and benefits of a climate changing under both natural and human influences must be weighed against the costs, efficacy, and collateral impacts of any "climate action", considering the nation's need for reliable and affordable energy with minimal local pollution. Beyond continuing precise, un-interrupted observations of the global climate system, it will be important to make realistic assumptions about future emissions, re-evaluate climate models to address biases and uncertainties, and clearly acknowledge the limitations of extreme event attribution studies. An approach that acknowledges both the potential risks and benefits of CO_2, rather than relying on flawed models and extreme scenarios, is essential for informed and effective decision-making.

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PREFACE

This document originated in late March 2025 when Secretary Wright assembled an independent group to write a report on issues in climate science relevant for energy policymaking, with particular focus on the question of whether carbon dioxide emissions endanger the U.S. public. We agreed to undertake the work on the condition that there would be no editorial oversight by the Secretary, the Department of Energy, or any other government personnel. This condition has been honored throughout the process and the writing team has worked with full independence.

The group began working in early April with a deadline of May 28. The short timeline and the technical nature of the material meant that we could not comprehensively review all topics. Rather, we chose to focus on topics that are treated by a serious, established academic literature; that are relevant to our charge; that are downplayed in, or absent from, recent assessment reports; and that are within our competence.

While the report is intended to be accessible to non-experts, we have omitted some introductory or explanatory material that can easily be accessed elsewhere. Nor have we attempted to survey entire literatures related to the topics covered. We have focused as much as possible on literature published since 2020 and referenced previous IPCC and NCA assessment reports. We have also used data through 2024 where possible.

The writing team is grateful to Secretary Wright for the opportunity to prepare this report and for his support of independent scientific assessment and open scientific debate.

John Christy, Ph.D.

Judith Curry, Ph.D.

Steven Koonin, Ph.D.

Ross McKitrick, Ph.D.

Roy Spencer, Ph.D.

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PART I: DIRECT HUMAN INFLUENCE ON ECOSYSTEMS AND THE CLIMATE

1 CARBON DIOXIDE AS A POLLUTANT

Chapter summary:
Carbon dioxide (CO_2) differs in many ways from the so-called Criteria Air Pollutants. It does not affect local air quality and has no human toxicological implications at ambient levels. It is an issue of concern because of its potential effects on the global climate, a complex issue that occupies much of this report.

The Clean Air Act of 1970 defined six so-called Criteria Air Contaminants subject to regulation (EPA): particulate matter, ground-level ozone, sulfur dioxide, nitrogen dioxide, lead, and carbon monoxide. In 2007, the Supreme Court ruled that greenhouse gases (CO_2 among them) were also "pollutants" subject to regulation under Clean Air Act (Mass. v. EPA, 2007). While the definition of "pollutant" is ultimately a legal matter, there are important scientific distinctions between CO_2 and the Criteria Air Contaminants. The latter are subject to regulatory control because they cause local problems depending on concentrations that include nuisances (odor, visibility), damage to plants, and, at high enough exposure levels, toxicological effects in humans. In contrast, CO_2 is odorless, does not affect visibility and has no toxicological effects at ambient levels. It is a naturally occurring part of the atmosphere and a key component of human and plant respiration. CO_2 is essential for plant photosynthesis and higher levels are beneficial for vegetation. In these aspects, CO_2 is similar to water vapor.

Ambient outdoor air today contains about 430 parts per million (ppm) CO_2, increasing at about 2 ppm per year. The U.S. Occupational Safety and Health Administration issues guidelines for indoor workplaces in which elevated CO_2 might be encountered, such as where dry ice is used. The Permissible Exposure Limit is 5,000 ppm over 8 hours (OSHA, 2024). Allen *et al.* (2015) reported evidence of diminished performance on some cognitive tasks among workers in office cubicles when exposed to CO_2 levels above 1,000-1,500 ppm. These levels are far larger than any plausible ambient outdoor value through the end of the 22nd century.

The growing amount of CO_2 in the atmosphere directly influences the earth system by promoting plant growth (global greening), thereby enhancing agricultural yields, and by neutralizing ocean alkalinity. But the primary concern about CO_2 is its role as a greenhouse gas (GHG) that alters the earth's energy balance. How the climate will respond to that influence is a complex question that will occupy much of this report.

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2 DIRECT IMPACTS OF CO_2 ON THE ENVIRONMENT

Chapter summary:
CO_2 enhances photosynthesis and improves plant water use efficiency, thereby promoting plant growth. Global greening due to increased CO_2 levels in the atmosphere is well-established on all continents.

CO_2 absorption in sea water makes the oceans less alkaline. The recent decline in pH is within the range of natural variability on millennial time scales. Most ocean life evolved when the oceans were mildly acidic. Decreasing pH might adversely affect corals, although the Australian Great Barrier Reef has shown considerable growth in recent years.

2.1 CO_2 and global greening

The growing CO_2 concentration in the atmosphere has the important positive effect of promoting plant growth by enhancing photosynthesis and improving water use efficiency. That is evident in the "global greening" phenomenon discussed below, as well as in the improving agricultural yields discussed in Chapter 10.

2.1.1 Measurement of global greening

"Greening" refers to an increase in the fraction of the Earth's surface covered by plants. It can be quantified by the "Leaf Area Index" (LAI) measured by satellite. Many studies over the past decade have confirmed a global greening pattern (increase in LAI) attributable to rising CO_2 levels. Zhu *et al.* (2016) was one of the first studies to report that global greening was detectable using satellite sensors. From 1982 to 2011 they detected greening over 25-50 percent of the Earth versus "browning" over only four percent and attributed 70 percent of the greening to rising CO_2 levels (see Figure 2.1).

Zheng *et al.* (2017) confirmed the pattern, noting that greening over thirty years had added 8 percent to global leaf area and that greening was mitigating warming. Greening has been observed globally but Chen *et al.* (2019) noted that China and India were exploiting it through land management changes. Thus, while China accounts for only 6.6 percent of global vegetated area it accounts for 25 percent of global net increase in LAI. Piao *et al.* (2020) noted that greening was even observable in the Arctic.

While plant models predict increased photosynthesis in response to rising CO_2, Haverd *et al.* (2020) reported a CO_2 fertilization rate nearly double model predictions. That is, CO_2 fertilization had driven an increase in observed global photosynthesis by 30 percent since 1900, versus 17 percent predicted by plant models. This indicates that global models of the socioeconomic impacts of rising CO_2 have likely understated the benefits to crops and agriculture. The connection between CO_2 fertilization and agriculture will be discussed in Chapter 9.

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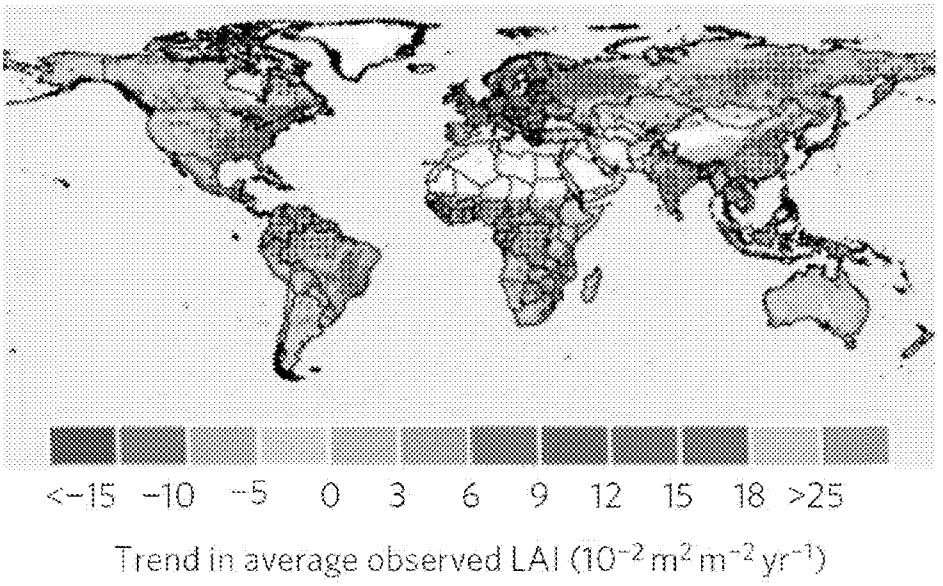

Figure 2.1: Trends in average Leaf Area Index (LAI). Source: Zhu *et al.* 2016 Figure 3.

Finally, Chen *et al.* (2024) surveyed claims that greening had slowed since 2000 due to drought stress. They found instead that faulty satellite sensors were the cause and that the corrected data showed accelerated greening over 55 percent of the globe while browning was accelerating over only 7 percent. In other words, the greening trend continued with no evidence of slowdown, and CO_2 fertilization remained the dominant driver

2.1.2 Photosynthesis and CO_2 levels

Plants build biomass through *photosynthesis,* a process that converts carbon dioxide, water, and light into sugar. The plant enzyme responsible for photosynthesis is Ribulose-1,5-bisphosphate-carboxylase/oxygenase or "Rubisco". Photosynthesis is initiated when CO_2 is available at the surface of the Rubisco enzyme where it is converted to a molecule with 3 carbon atoms and thereafter incorporated into plant mass. This is referred to as the "C3" process.

Rubisco is estimated to have evolved about 3 billion years ago. Over geological time the Earth's atmospheric CO_2 levels were usually many times higher than they are today, as shown in Figure 2.2.

About 400 million years ago CO_2 levels were an estimated 2,000-4,000 ppm and were at or above 1,000 ppm for much of the interval from 200 to 50 million years ago (Berner 2006, Judd *et al.* 2024). Over the past 35 million years the level of atmospheric CO_2 has been steadily declining, falling to as low as 170 ppm during glaciations (Gerhart and Ward 2010).

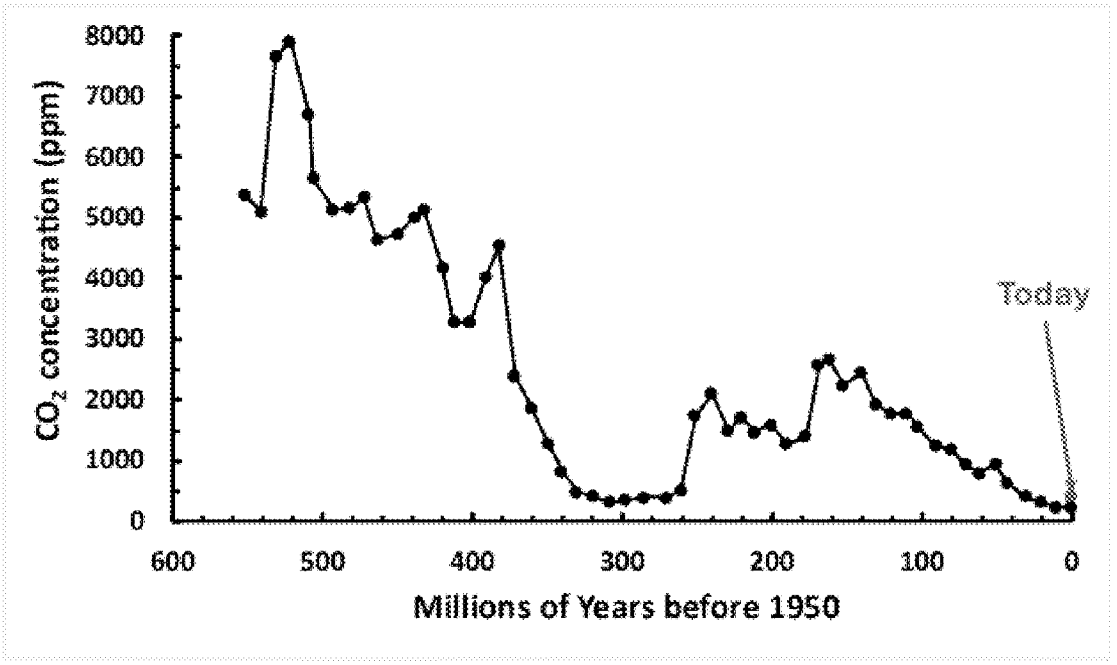

Figure 2.2. Ambient CO_2 levels over the past 550 million years. Today's concentration of 430 ppm is also shown. Source: (Berner 2006)

In response to low-CO_2 conditions some plants evolved another photosynthetic pathway called C4, in which CO_2 is concentrated in the vicinity of Rubisco, allowing for the C3 process to function more efficiently. For agricultural purposes the plant categories are:

- C3: rice, wheat, soybeans and most other crops
- C4: maize (corn), sugar cane, millet, sorghum

Had atmospheric CO_2 levels continued declining, plant growth would have declined and eventually ceased. Below 180 ppm, the growth rates of many C3 species are reduced 40-60 percent relative to 350 ppm (Gerhart and Ward 2010) and growth has stopped altogether under experimental conditions of 60—140 ppm CO_2. Some C4 plants are still able to grow at levels even as low as 10 ppm, albeit very slowly (Gerhart and Ward 2010).

Current CO_2 levels are about 430 ppm, up from 280 ppm in the early 1800s. The positive response of plants to extra CO_2 is illustrated in Figure 2.3, reproduced from Gerhart and Ward (2010). It shows the growth effect of CO_2 on Velvetleaf (*Abutilon theophrasti*) seedlings over 14 days under controlled conditions where only the CO_2 exposure is varied. The gains induced by increasing CO_2 from 150 ppm to 350 ppm continue under a further doubling to 700 ppm.

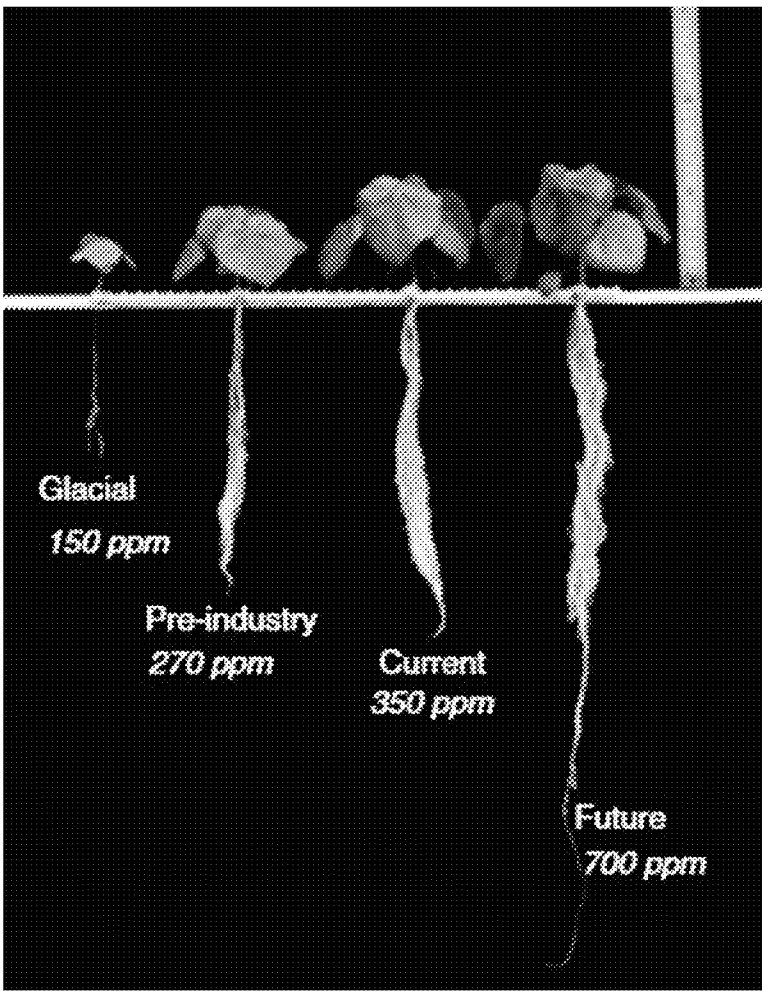

Figure 2.3: growth of *Abutilon theophrasti* after 14 days under identical conditions but for the indicated variations in CO_2 levels. Source: Gerhart and Ward (2010). Note "Current" corresponds to 1988 in image.

Over the past 60+ years there have been thousands of studies on the response of plants to rising CO_2 levels. The overwhelming theme is that plants, especially C3 plants, benefit from extra CO_2. There are two mechanisms by which CO_2 confers a growth benefit:

- Enhanced photosynthesis via the metabolic pathways described above.
- Increased water use efficiency. This arises because plants draw in CO_2 by opening the stomata (pores) on the leaf surface. When CO_2 is scarce the stomata must be kept wide open for long periods, allowing water to evaporate. Under enriched CO_2 conditions the stomata remain closed for longer periods, thus helping the plant retain water longer, and so increasing water use efficiency.

Specific effects of climate change on U.S. agriculture will be reviewed in Chapter 9.

2.1.3 Rising CO_2 and crop water use efficiency

Derying *et al.* (2016) surveyed evidence on crop water productivity (CWP), the yield per unit of water used, drawing attention to the potential for CO_2 both to enhance photosynthesis and to reduce leaf-level transpiration (water loss during leaf respiration). They surveyed all available FACE data (Free Air CO_2 Enrichment—see Chapter 9) on crop yield changes for maize (corn), wheat, rice, and soybean and combined

it with crop model data simulating yield responses as of 2080 under the extreme RCP8.5 emissions scenario in four growing regions (Tropics, Arid, Temperate and Cold) each of which were split into rainfed and irrigated sub-regions. They reported that models without CO_2 fertilization predicted CWP losses in every region, but those were more than offset by CO_2 fertilization so that all regions showed a net CWP gain. Deryng *et al.* (2016) also reported that negative impacts of warming on wheat and soybean yields were fully offset by CWP gains and mitigated by up to 90 percent for rice and 60 percent for maize.

Similarly, Cheng *et al.* (2017) noted that increased global plant growth from 1982 to 2011 due to rising CO_2 uptake was accompanied by such large gains in CWP that global water use by plants had not increased, despite the extra biomass.

Deryng *et al.* (2016) assumed that climate change would "exacerbate water scarcity". Yet while models do predict that drylands will expand under climate warming, current data show the opposite: greening is happening even in arid areas. Zhang *et al.* (2024) report that due to increased CO_2 levels "increasing aridity in drylands won't lead to a general loss of vegetation productivity"; at most only 4 percent of currently arid areas will see increased desertification.

2.1.4 CO_2 fertilization benefits in IPCC Reports

The IPCC has only minimally discussed global greening and CO_2 fertilization of agricultural crops. The topic is briefly acknowledged in a few places in the body of the IPCC 6th and earlier Assessment Reports but is omitted in all Summary documents. Section 2.3.4.3.3 of the AR6 Working Group I report, entitled "global greening and browning," points out that the IPCC Special Report on Climate Change and Land had concluded with *high confidence* that greening had increased globally over the past 2-3 decades. It then discusses that there are variations in the greening trend among data sets, concluding that while they have *high confidence* greening has occurred, they have *low confidence* in the magnitude of the trend. There are also brief mentions of CO_2 fertilization effects and improvements in water use efficiency in a few other chapters in the AR6 Working Groups I and II Reports.

Overall, however, the Policymaker Summaries, Technical Summaries, and Synthesis Reports do not discuss the topic.

2.2 The Alkaline Oceans

2.2.1 Changing pH

A neutral aqueous solution has a pH of 7.0, while one with pH greater than 7.0 is alkaline (also termed basic) and with pH less than 7.0 is acidic. The modern-day global average pH of sea water is estimated to be 8.04 (Copernicus Marine Service 2025), down from an estimated value of 8.2 in pre-Industrial times (Gattuso and Hansson, 2011). As CO_2 concentrations in the atmosphere increased, the oceans absorbed more, which decreases their pH. Depending upon the oceans' buffering capacity, they are expected to become somewhat less alkaline over time, consistent with the observed decrease in pH.

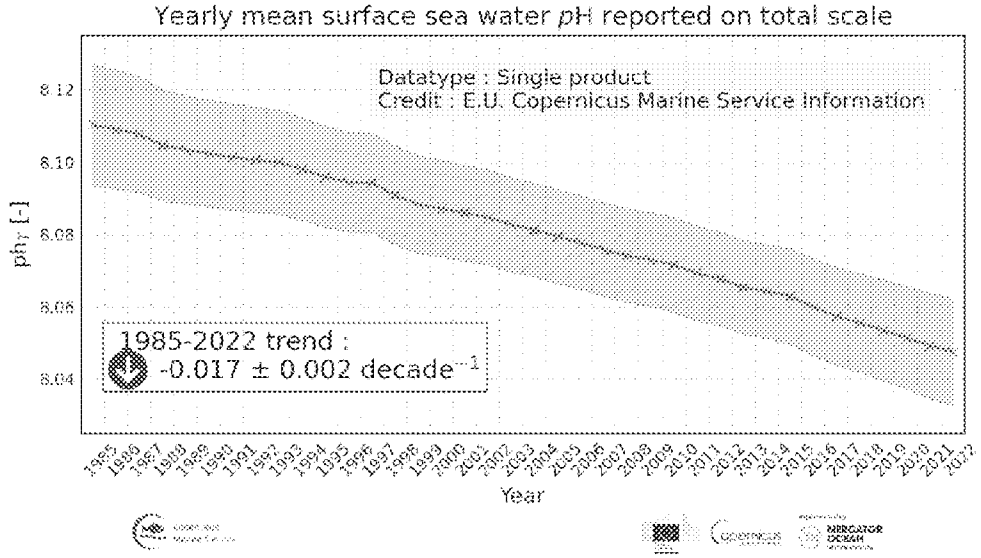

Figure 2.4: Ocean pH 1985 – 2022. Source: Copernicus Marine Service 2025

While this process is often called "ocean acidification", it is a misnomer because the oceans are not expected to become acidic; "ocean neutralization" would be more accurate. Even if the water were to turn acidic, it is believed that life in the oceans evolved when the oceans were mildly acidic with pH 6.5 to 7.0 (Krissansen-Totton *et al.*, 2018). On the time scale of thousands of years, boron isotope proxy measurements show that ocean pH was around 7.4 or 7.5 during the last glaciation (up to about 20,000 years ago) increasing to present-day values as the world warmed during deglaciation (Rae *et al.*, 2018). Thus, ocean biota appear to be resilient to natural long-term changes in ocean pH since marine organisms were exposed to wide ranges in pH.

2.2.2 Coral reef changes

There are concerns that a decreasing pH of sea water will reduce the calcification rate of coral reefs. But coral reefs already endure large swings in pH, partly due to daily photosynthetic activity in the reef; measured pH values range from 9.4 during the day to 7.5 at night (Revelle and Fairbridge, 1957). De'ath *et al.* (2009) reported that a portion of Australia's Great Barrier Reef (GBR, the world's largest coral reef ecosystem) had experienced a 14 percent decline in calcification since 1990. This was tentatively attributed to increasing water temperature and decreasing pH. But Ridd *et al.* (2013) showed that report to have resulted from a biased data analysis that, when corrected, showed no change in calcification rates. Nevertheless, the alarm produced by the original paper has persisted as evidenced by the large number of published citations (541) to the original study compared to only 11 citations to the correction (as of 30 April 2025).

The most recent annual summary of GBR conditions from the Australian Institute of Marine Science indicates that coral production has rebounded strongly (AIMS, 2023). Figure 2.5 shows the results of the AIMS surveys of hard coral cover, expressed as a percentage of the reef area. Much of the decline in the GBR before 2011 turned out to be due to intense tropical cyclone activity (Beeden *et al.*, 2015) as well as a string of marine heatwaves, agricultural runoff and invasive species (Woods Hole, 2023). Given the reported declines in GBR calcification between 1990 and 2009 and the continued increase in atmospheric CO_2 levels the rebound has surprised some observers.

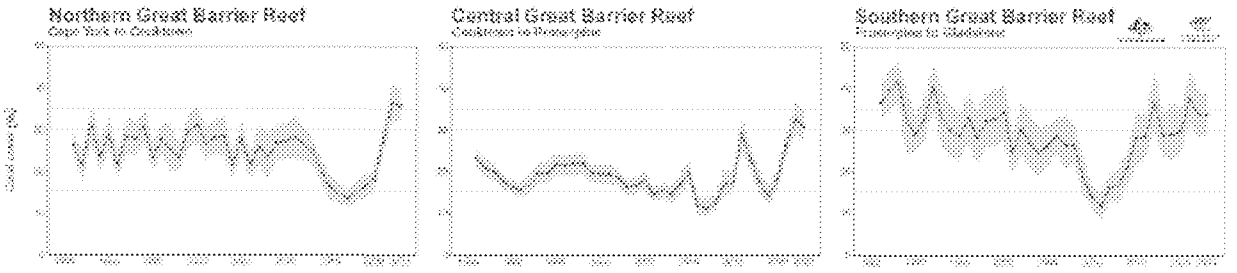

Figure 2.5 Hard coral cover of three regions of the Great Barrier Reef 1985 to 2023. Source: AIMS 2023.

It is being increasingly recognized that publication bias (alarming ocean acidification results preferred by high-impact research publications) exaggerates the reported impacts of declining ocean pH. An ICES Journal of Marine Science Special Issue addressed this problem with an article entitled, *Towards a Broader Perspective on Ocean Acidification Research*. In the Introduction to that Special Issue, H. I. Browman stated, "As is true across all of science, studies that report no effect of ocean acidification are typically more difficult to publish." (Browman, 2016).

Similarly, a meta-analysis (Clements *et al.*, 2021) of the negative effects of ocean acidification on reef fish behavior found what they called a "decline effect": initially dramatic conclusions published in prominent journals showing apparently large impacts of acidification tended to be followed up by subsequent studies on larger sample sizes yielding much smaller and typically non-existent effects. They call for their colleagues to improve research practices to counter the "decline effect":

> [The] vast majority of studies with large effect sizes in this field tend to be characterized by low sample sizes, yet are published in high-impact journals and have a disproportionate influence on the field in terms of citations. We contend that ocean acidification has a negligible direct impact on fish behavior, and we advocate for improved approaches to minimize the potential for a decline effect in future avenues of research (Clements *et al.*, 2021).

In summary, ocean life is complex and much of it evolved when the oceans were acidic relative to the present. The ancestors of modern coral first appeared about 245 million ago; as can be seen from Figure 2.2, CO_2 levels for more than 200 million years afterward were many times higher than they are today. Much of the public discussion of the effects of ocean "acidification" on marine biota has been one-sided and exaggerated. There is a known tendency for studies reporting dramatic effects on things like coral cover and fish behavior to get published in high-impact journals and receive widespread press coverage, then subsequent research rebutting those findings receives little attention.

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3 HUMAN INFLUENCES ON THE CLIMATE

Chapter Summary:

The global climate is naturally variable on all time scales. Anthropogenic CO_2 emissions add to that variability by changing the total radiative energy balance in the atmosphere.

The IPCC has downplayed the role of the sun in climate change but there are plausible solar irradiance reconstructions that imply it contributed to recent warming.

Climate projections are based on IPCC emission scenarios that have tended to exceed observed trends. Most academic climate impact studies in recent years are based upon the extreme RCP 8.5 scenario that is now considered implausible; its use as a business-as-usual scenario has been misleading.

Carbon cycle models connect annual emissions to growth in the atmospheric CO_2 stock. While models disagree over the rate of land and ocean CO_2 uptake, all agree that it has been increasing since 1959.

3.1 Components of radiative forcing and their history

3.1.1 Historical radiative forcing

A changing climate has been the norm throughout the Earth's 4.6-billion-year history. The Earth's temperature and weather patterns change naturally over timescales ranging from decades to millions of years. Natural variations in the surface climate originate in two ways. Internal climate fluctuations associated with circulations in the atmosphere and ocean exchange energy, water, and carbon between the atmosphere, oceans, land, and ice. External influences on the climate system include variations in the energy received from the sun and the effects of volcanic eruptions. Human activities influence climate through changing land use and land cover. Humans are also changing the composition of the atmosphere by emissions of CO_2 and other greenhouse gases and by altering the concentration of aerosol particles in the atmosphere.

The earth is warmed by the sunlight it absorbs and is cooled by the heat it radiates to space. Averaged over the Earth's surface, each of these processes involve power flows of about 240 Watts per square meter (W/m^2). When they are in balance, there are no net external causes of warming or cooling. Both human and natural influences on the climate alter this balance and so cause the climate to change.

Influences on the Earth's energy balance at the top of the atmosphere are quantified by "radiative forcing", the extent to which they disturb the warming/cooling balance; a positive forcing warms while a negative forcing cools. The IPCC's estimated history of major components of radiative forcing since 1750 is shown in the following two figures from its AR6.

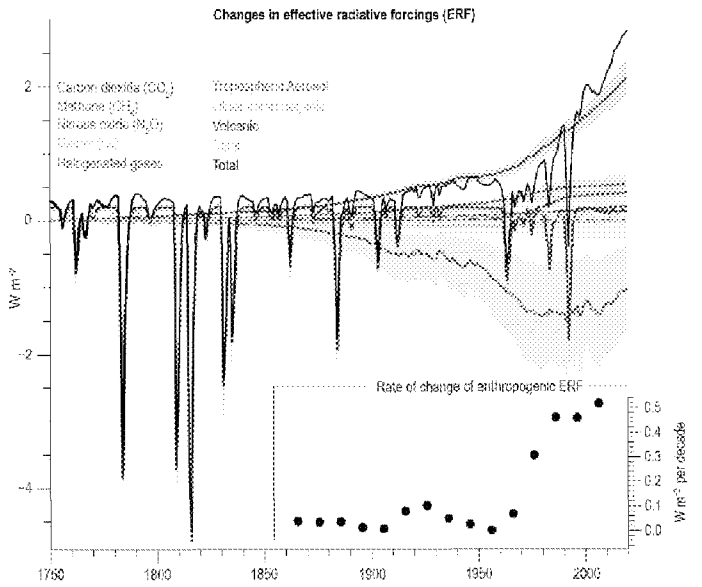

Figure 3.1.1: IPCC estimates of radiative forcing components over time. Shading indicates uncertainty ranges. Source: AR6 WGI Ch2 Fig. 10

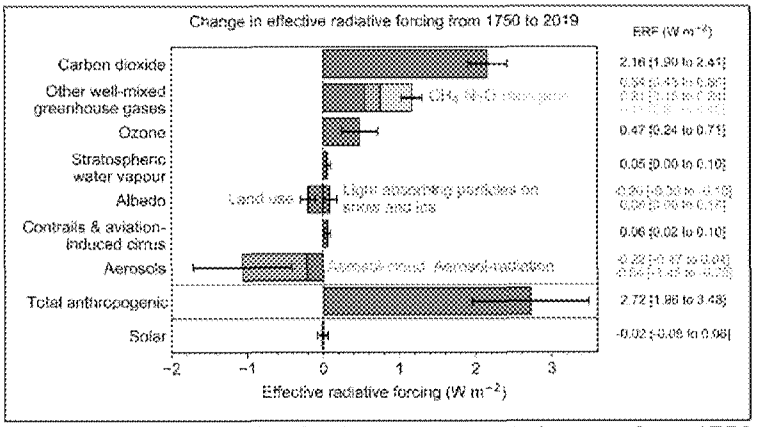

Figure 3.1.2 IPCC estimates of radiative forcing component changes from 1750 to 2019. Source: AR6 WGI Ch 7 Fig. 7-6.

These graphs show that the total radiative forcing is comprised of both natural and anthropogenic components. Carbon dioxide is the largest human influence on the climate and the one most relevant to the influence of fossil fuel use. It exerts a warming influence by decreasing the cooling power of the atmosphere. Emissions of CO_2 are accumulating in the atmosphere, as described in the following section, so that the warming influence is growing. Other greenhouse gases (methane, nitrous oxide, halogens, and ozone) act similarly, currently adding another 75 percent to CO_2's warming. Aerosols exert an overall cooling effect, although with large uncertainties in the way they catalyze the formation of reflective clouds. As a result, understanding the causes of recent warming requires not just identifying the warming effects of CO_2, but also the more uncertain cooling effects of aerosols.

The IPCC assesses the change in the radiative forcing by the sun to be negligible, based on their preference for data reconstructions that imply minimal solar change since preindustrial times. But Connolly *et al.* (2021) reviewed sixteen different Total Solar Irradiance (TSI) reconstructions in the literature

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covering the years 1600-2000; the reconstructions vary from almost no change in TSI to a relatively large upward trend. Those authors note that the variation in TSI reconstructions combined with variations in surface temperature reconstructions allows for inferences consistent with either no or most 20th century warming being attributable to the sun.

A particularly thorny issue is the gap in TSI data between 1989 and 1991 due to a delay in the launch of a monitor following the Space Shuttle Challenger disaster on January 28 1986. This delay prevented a replacement satellite from being launched in time to overlap with, and its readings to be intercalibrated with, the prior system (Zacharias 2014, Scafetta *et al.* 2019). This is called the ACRIM (Active Cavity Radiometer Irradiance Monitor) gap problem. The question of whether there is an upward trend in TSI over 1978 to 2018 hangs on how the ACRIM data gap is filled. Connolly *et al.* (2021) found that the IPCC's consensus statements on solar forcing were formulated prematurely through the suppression of dissenting scientific opinions.

Another natural radiative forcing component is volcanic aerosols, which exert an episodic cooling influence. Box 4.1 in the IPCC AR6 Report addresses the climate impact of volcanic eruptions, noting three explosive volcanic eruptions that occurred in the first half of the 19th century. This included the 1815 Tambora eruption that resulted in the 'year without summer', with multiple harvest failures across the Northern Hemisphere. There is uncertainty about the sign of the relatively small forcing due to the submarine volcano Hunga Tonga which erupted in 2022 (Jenkins *et al.* 2023, Schoeberl *et al.* 2024).

Figure 3.1.1 shows that the anthropogenic forcing component was negligible before about 1900 and has increased steadily since, rising to almost 3 W/m^2 today. However, this is still only about 1 percent of the unperturbed radiation flows, making it a challenge to isolate the effects of anthropogenic forcing; state-of-the-art satellite estimates of global radiative energy flows are only accurate to a few W/m^2.

Natural sources of global energy imbalance other than volcanoes and total solar irradiance (TSI) are not included in these graphs because they remain largely unknown.

3.1.2 Change in atmospheric CO_2 since 1958

Carbon dioxide's warming influence depends on how much "extra" CO_2 accumulates in the atmosphere- *i.e.*, its concentration above the preindustrial value of 280 ppm. The CO_2 level as recorded at the Mauna Loa observatory in Hawaii, generally used as the representative global average concentration, is available online at https://gml.noaa.gov/ccgg/trends/index.html. The concentration was about 316 ppm at the start of the record in 1959 and is now about 430 ppm, a 36 percent increase. At the end of the last glaciation CO_2 levels had fallen to about 180 ppm. As discussed in Chapter 2, C3 plants begin dying at CO_2 levels below about 140 ppm and C4 plants at levels below 100 ppm, so if CO_2 levels had continued falling plant life would have been imperiled.

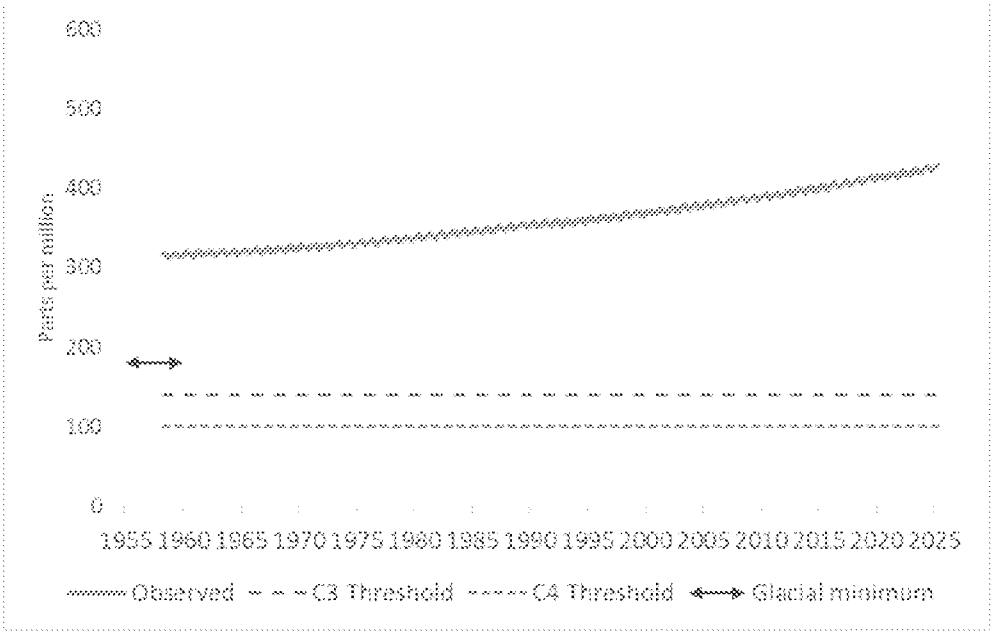

Fig. 3.1.3. Yearly average atmospheric CO_2 concentrations (1959-2025) in ppm measured at Mauna Loa (blue). C3 Threshold: Level below which C3 plants begin dying (140 ppm, see Chapter 2). C4 Threshold: Level below which C4 plants begin dying (100 ppm, see Chapter 2). Glacial minimum: Minimum level during recent glaciations (purple arrow). CO_2 data source: https://gml.noaa.gov/ccgg/trends/index.html

The annual increase in concentration is only about half of the CO_2 emitted because land and ocean processes currently absorb "excess" CO_2 at a rate approximately 50 percent of the human emissions. Future concentrations, and hence future human influences on the climate, therefore depend upon two components: (1) future rates of global human CO_2 emissions, and (2) how fast the land and ocean remove extra CO_2 from the atmosphere. We discuss each of these in turn.

3.2 Future emission scenarios and the carbon cycle

3.2.1 Emission scenarios

Assessing the dangers of future GHG emissions requires assumptions about what those emissions will be. Future emissions, and hence human influences on the climate, will depend upon future demographics, economic activity, regulation, and energy and agricultural technologies. Various assumptions about each of those lead to projections of greenhouse gas emissions and concentrations, aerosol concentrations, and changes in land use, which ultimately can be combined into assumptions about anthropogenic radiative forcing.

The great uncertainties about these many factors make it impossible to precisely predict future emissions. Instead, the IPCC has created various sets of scenarios meant to span a plausible range of possibilities for population, economy, and technologies. Recent versions of the scenarios are labeled by a number indicating the anthropogenic radiative forcing expected in 2100 under that scenario. Thus, a scenario labeled with a "6" corresponds to 6 W/m^2 of human-induced radiative forcing (warming) at the end of the century. (Recall current anthropogenic radiative forcing is about 2.7 W/m^2.)

Although the IPCC does not claim its emission scenarios are forecasts, they are often treated as such. Comparisons of past scenario groups against observations show that IPCC emission projections tend to overstate actual subsequent emissions. For the IPCC Third and Fourth Assessment Reports a set of emission projections from the *Special Report on Emission Scenarios* was used; these were referred to as the SRES scenarios. McKitrick *et al.* (2012) showed that, when converted to per capita values, the SRES scenario emissions distribution was skewed upwards and incompatible with observed trends. McKitrick and Wood (2013) further showed that global energy market dynamics constrained global per capita CO_2 emissions to an extent not reflected in IPCC scenarios. The bias of the SRES scenarios was confirmed by the later analysis of Hausfather *et al.* (2019) who showed that observed atmospheric CO_2 concentrations tracked the low end of the SRES range and also of subsequent IPCC scenario ranges (Figure 3.2.1).

For AR5 the IPCC developed a new set of scenarios called the Representative Concentration Pathways (RCPs). These were identified by a number representing the increase in forcing and were thus called RCP2.6, RCP4.5, RCP6.0 and RCP8.5. RCP2.6 (implying an anthropogenic radiative forcing in 2100 of 2.6 W/m^2) describes a GHG concentration pathway leading to warming well below 2°C. At the other end of the scale RCP8.5 is an extreme outcome implying nearly 5°C warming from 1900 to 2100.

RCP8.5 came to be referred to as the no-policy baseline, or "business-as-usual" scenario in both the academic literature and popular media. It was therefore used to generate the reference outcome supposedly representing the 21st century world in the absence of increasingly stringent emission reduction policies. But RCP8.5 was intended as a low-probability high emissions scenario and its use as a business-as-usual baseline has been criticized as grossly misleading.[1] Hausfather and Peters (2020) writing in a commentary in *Nature*, pointed out that RCP8.5 was developed as an extreme worst-case, and its misuse as a "business as usual" baseline has resulted in a large number of misleading studies and media reporting.

The implausibility of the RCP8.5 scenario was examined by Burgess *et al.* (2021). They noted that RCP8.5 has already diverged from observed trends in energy use and the near future trends diverge sharply from those of the International Energy Agency (IEA), which provides market-based projections of energy use for the coming decades. The IEA trends, which are based on plausible extrapolations of current economic and demographic trends, run below the entire envelope of RCP projections, implying not only that RCP8.5 is dubious, but that even lower emission scenarios are unlikely.

Widespread use of RCP8.5 has created a bias towards alarm in the climate impacts literature. The extent of this problem was confirmed in a literature analysis by Pielke Jr. and Ritchie (2020). They found that some 16,800 scientific papers published between 2010 and 2020 used the RCP8.5 scenario, with about 4,500 of the articles linking RCP8.5 to the concept of "business-as-usual". Their analysis showed how RCP8.5 was misused not only by individual researchers, but also by influential science agencies like the IPCC and the U.S. National Climate Assessment (USNCA), which has directly led to misleading coverage in prominent media outlets.

[1] This extreme scenario is useful for modelers, since a large forcing generates a large response (warming) making it easier to assess a model's sensitivity. But that's very different than claiming it is a plausible future outcome.

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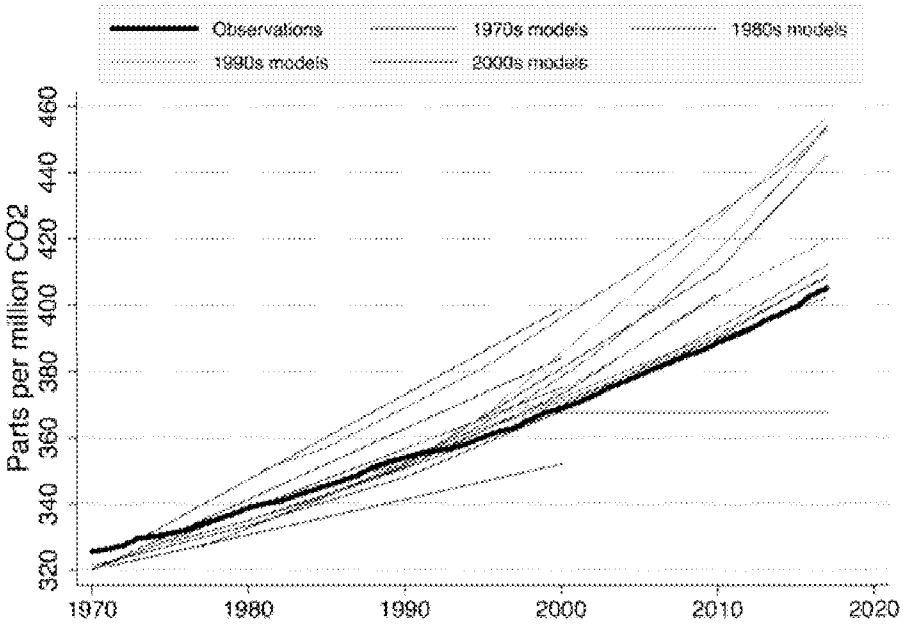

Figure 3.2.1 Comparison of observed atmospheric CO_2 levels (black line) with scenario projections (colored lines, mainly IPCC) since the 1970s. Source: Hausfather *et al.* (2019) Figure S4.

Pielke and Ritchie (2020) reported new studies using RCP8.5 were published at a rate of about 20 per day, with about two per day specifically linking RCP8.5 and "business as usual." They conclude that the climate research community has spent a decade "committing scientific resources to science fiction" and that "The scientific literature has become imbalanced in an apocalyptic direction."

The IPCC developed a new set of scenarios for AR6, the "Shared Socioeconomic Pathway" (SSP) scenarios, which have continued the bias shown in the RCP and SRES scenarios. Figure 3.2.2 shows total global observed CO_2 emissions compiled by the International Energy Agency (IEA) merged with the emission projection from the EIA taking account of energy use projections and current policies. The other lines show the range of IPCC SSP scenarios (SSP1-SSP5). As of 2023, global CO_2 emissions have been tracking well below SSP7.0 and are even below SSP2-4.5.

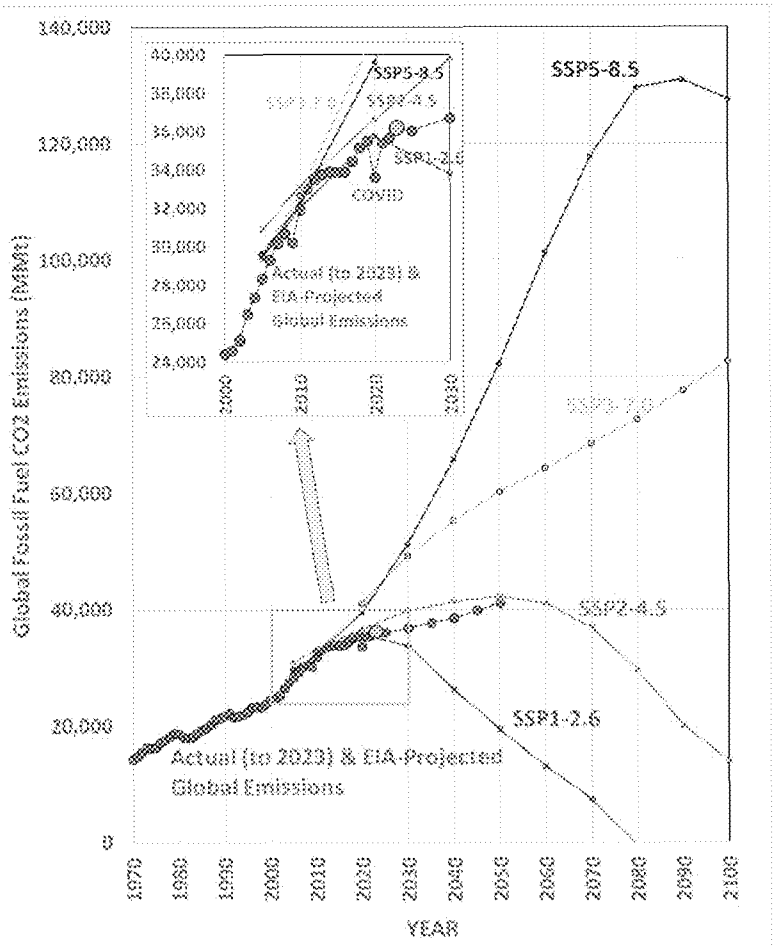

Figure 3.2.2. Observed and projected CO2 emissions. Source: IPCC (SSP scenarios) and Energy Information Administration (EIA). Green: observed historical emissions and EIA projections. Other lines: SSP1-5. Data source: Friedlingstein *et al.* (2024).

3.2.2 The carbon cycle relating emissions and concentrations

Carbon dioxide emissions from fossil fuel burning (and to a lesser extent deforestation and cement production) have led to steadily increasing CO_2 concentrations in the atmosphere, as shown in Fig. 3.1.3. The relation between emissions and concentration is determined by the global carbon cycle of land and ocean processes that exchange carbon with the atmosphere. Our understanding of these processes was reviewed by Crisp *et al.* (2021).

There are about 850 Gt of carbon (GtC) in the Earth's atmosphere[2], almost all of it in the form of CO_2. Each year, biological processes (plant growth and decay) and physical processes (ocean absorption and outgassing) exchange about 200 GtC of that carbon with the Earth's surface (roughly 80 GtC with the land and 120 GtC with the oceans). Before human activities became significant, removals from the atmosphere were roughly in balance with additions. But burning fossil fuels (coal, oil, and gas) removes carbon from the ground and adds it to the annual exchange with the atmosphere. That addition (together with a much

[2] Because CO_2 is chemically transformed through the course of the carbon cycle, it is more convenient to track atoms of carbon rather than molecules of CO_2. One gigatonne of carbon (GtC) is equivalent to about 3.7 Gt of CO_2.

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smaller contribution from cement manufacturing) amounted to 10.3 GtC in 2023, or only about 5 percent of the annual exchange with the atmosphere.

The carbon cycle accommodates about 50 percent of humanity's small annual injection of carbon into the air by naturally sequestering it through plant growth and oceanic uptake, while the remainder accumulates in the atmosphere (Ciais *et al.*, 2013). For that reason, the annual increase in atmospheric CO_2 concentration averages only about half of that naively expected from human emissions.

To project future CO_2 concentrations in the atmosphere, and hence future human influences on the climate, it is important to know how the carbon cycle might change in the future. The historical near constancy of that 50 percent fraction means that the more CO_2 humanity has produced, the faster nature removed it from the atmosphere. That 50 percent fraction changes somewhat from year to year due to natural carbon cycle imbalances from El Nino, La Nina, and varying weather patterns. There was also a substantial additional reduction in atmospheric CO_2 after the 1991 eruption of Mt. Pinatubo, a curious result that has yet to be explained (Angert *et al.*, 2004).

The main processes that remove excess CO_2 from the atmosphere are increased growth of land vegetation (especially at high latitudes), some increase in the sequestering of carbon in soils, and uptake of CO_2 by the ocean due to the increasing partial pressure of atmospheric CO_2 over that of CO_2 dissolved in the ocean. All twenty land carbon cycle models tracked by the Global Carbon Project (Friedlingstein *et al.*, 2024) show land processes have been removing excess CO_2 at an increasing rate since 1959. This is consistent with a "global greening" phenomenon (Chapter 2.1) observed by satellites since monitoring of global greenness began in 1982.

While land vegetation has been responding positively to more atmospheric CO_2, uptake of extra CO_2 by ocean biological processes remains too uncertain to be measured reliably. Our current understanding of these and many more carbon cycle processes was reviewed by Crisp *et al.* (2021).

CO_2 uptake by land processes

The uptake of extra CO_2 from the atmosphere by land surface processes (as also inferred from global greening) has been modeled with 20 different dynamic global vegetation models, the outputs of which are updated every year by the Global Carbon Project (Friedlingstein, 2024). As seen in Fig. 3.2.3, all of those models agree that vegetation and soils have been sequestering carbon from the atmosphere. But we also see that the long-term trends over 1959 to 2023 (65 years) vary widely between models, by nearly a factor of 7. This demonstrates that there remains considerable uncertainty in how fast land processes are removing CO_2 from the atmosphere, which in turn creates uncertainty in future atmospheric CO_2 concentrations, which then produce uncertainty in climate model simulations of future climate change.

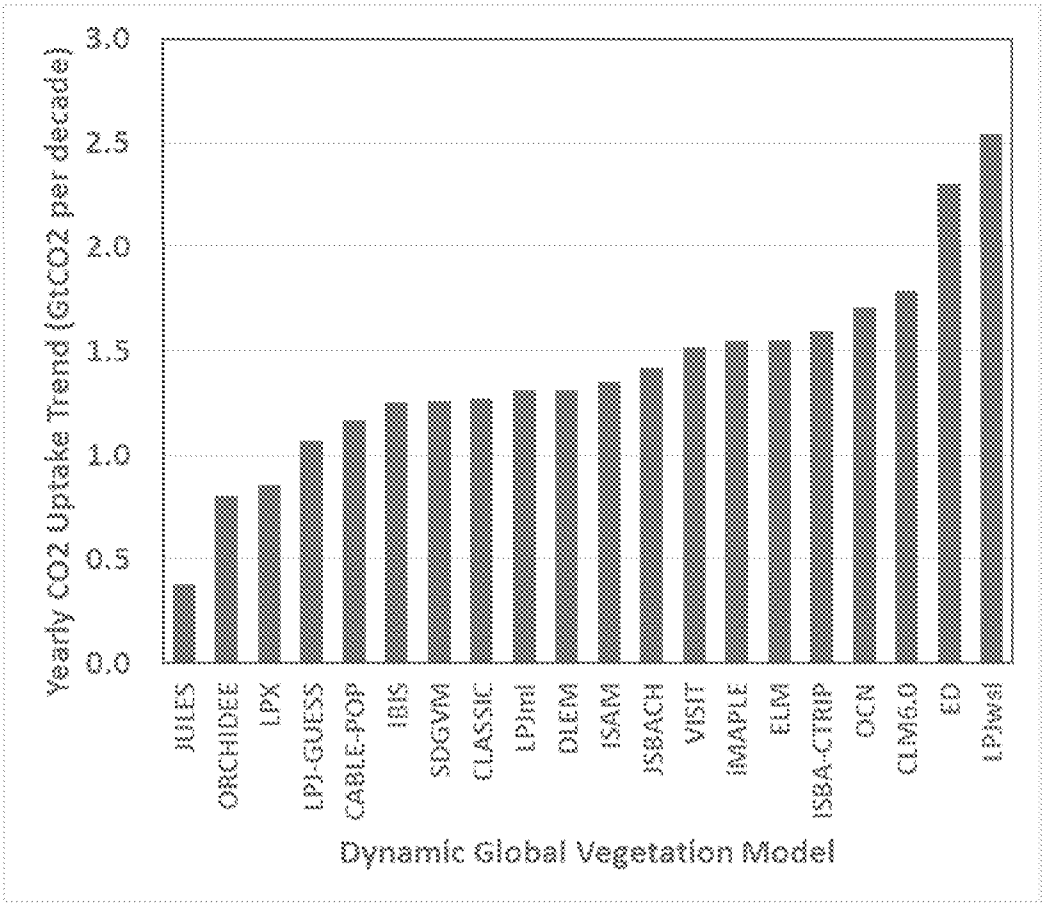

Figure 3.2.3 Trends of annual CO_2 uptake (GtCO2 per year per decade) by land processes during 1959-2023 simulated by 20 different dynamic global vegetation models periodically reported by the Global Carbon Project (Friedlingstein, 2024).

CO_2 uptake by ocean processes

The uptake of extra CO_2 from the atmosphere by ocean processes has been modeled with 10 different ocean biogeochemistry models, the outputs of which are updated every year by the Global Carbon Project (Friedlingstein, 2024). Like the results from the land models, all of the ocean models agree that the global oceans have been sequestering carbon from the atmosphere at an increasing rate during 1959-2023 (Fig. 3.2.4). Unlike the land models, however, the ocean models show much better agreement with each other, with the model producing the fastest increasing CO_2 uptake being only 65 percent faster than the model with the most slowly increasing CO_2 uptake. In spite of the relative agreement among models, Friedlingstein *et al.* (2022) notes that there is substantial discrepancy between the different methods on the strength of the ocean sink over the last decade, particularly in the Southern Ocean.

Note that the average trend in CO_2 uptake across all land models in Fig. 3.2.3 is 25 percent larger than the average trend in ocean uptake. This suggests land processes are increasing in their ability to remove CO_2 faster than ocean processes are increasing their CO_2 sequestration.

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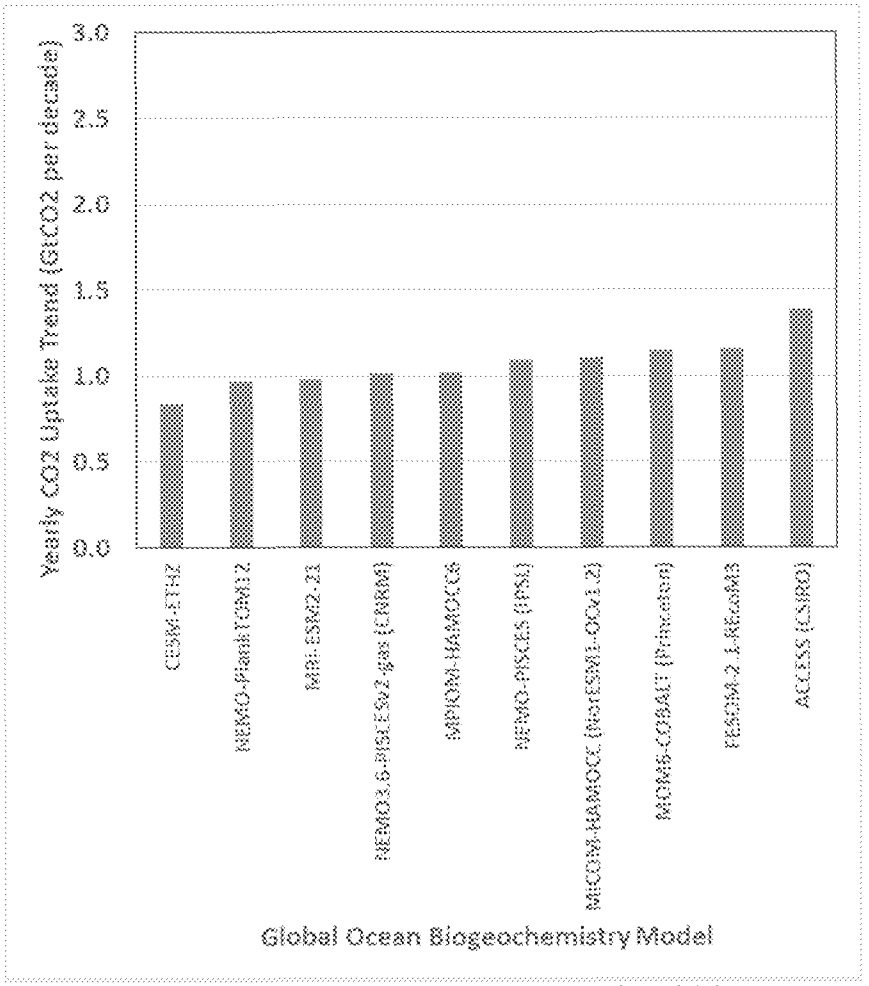

Figure 3.2.4 Trends of annual CO_2 uptake (GtCO2 per year per decade) by ocean processes during 1959-2023 simulated by 10 different ocean biogeochemistry models periodically reported by the Global Carbon Project (Friedlingstein, 2024).

3.3 Urbanization influence on temperature trends

Historical temperature data over land has been collected mainly where people live. This raises the problem of how to filter out non-climatic warming signals due to Urban Heat Islands (UHI) and other changes to the land surface. If these are not removed the data might over-attribute observed warming to greenhouse gases. The IPCC acknowledges that raw temperature data are contaminated with UHI effects but claims to have data cleaning procedures that remove them. It is an open question whether those procedures are sufficient.

AR6 downplayed this issue by saying (WGI p. 235) that no recent evidence had emerged to alter the AR5 finding that urbanization causes an upward bias of no more than 10 percent in the global land surface warming trend. AR5 (WGI p. 189) also cited the 10 percent upper bound without citing a source. AR4 (WGI p. 244) cited Jones *et al.* (1990) and Peterson *et al.* (1999) as the basis of the claim. Peterson *et al.* had failed to find any difference in trends between rural and urban samples, although their definition of rural included local populations up to 10,000 persons while the relative influence of urbanization begins well below that (Spencer *et al.*, 2025). Jones *et al.* compared rural/urban warming in three regions: Eastern Australia, Eastern China and Western Soviet Union. Their definition of "rural" included towns of up to

10,000 in the former Soviet Union and up to 100,000 in China. They found relative warming biases greater than 10 percent in these areas but conjectured that the urbanization effect averaged over the areas they did not examine would bring the global land bias to under 10 percent of the observed warming trend.

Several papers appeared in print prior to the IPCC AR4 that argued that the warming effect of UHIs added a relatively large (30-50%) component to observed warming and was not simulated by climate models (de Laat and Maurellis 2006, McKitrick and Michaels 2007). These findings were based on correlations between locations of maximum warming over land with locations of maximum socioeconomic development. AR4 asserted (p. 244) that these correlations were an artefact of natural atmospheric circulations and were in fact statistically insignificant, and on that basis set the findings aside. Their claim was controversial because it was presented with no supporting evidence. McKitrick (2010) and McKitrick and Nierenberg (2010) showed that taking into account various conjectured alternative explanations for the correlations did not affect their significance. AR5 (p. 189) conceded that AR4 had provided "no explicit evidence" for its assessment and further acknowledged, based on these papers, that there was "significant evidence for such contamination of the record" i.e. a warming bias in the land record. However as already noted, elsewhere in the AR5 report they carried forward AR4 claim that it was less than 10 percent of observed warming. Further they provided no caution about using the land record for climate measurement despite conceding the evidence for UHI contamination. Recently Soon *et al.* (2023) estimated an urbanization bias in the Northern Hemisphere land record over 1850-2018 sufficient to increase the trend in the blended record from 0.55°C to 0.89°C per century.

Some studies providing evidence against UHI contamination compared warming rates between rural and urban locations (Jones *et al.* 1990, Peterson *et al.* 1999, Wickham *et al.* 2013). It is not known whether such methods would be capable of detecting UHI bias even when present. The influence of UHI warming is logarithmic in population, in other words it is strongest at low population density then levels off as local urbanization expands (Oke 1973, Spencer *et al.* 2025). Hence failure to find a difference in warming rates between urban and rural stations does not prove the absence of UHI contamination. McKitrick (2013) provided an empirical demonstration in which the rural/urban trends were not significantly different in a data set shown on other grounds to be contaminated with UHI bias.

Parker (2006) examined a sample of urban locations and found no difference in trends between subsets partitioned according to nighttime wind speed, concluding on this basis that urbanization could not be a significant factor. Here again the question is whether such a method would find UHI bias even if present. McKitrick (2013) presented an example in which UHI-contaminated data did not exhibit significant trend differences when stratified according to wind speed.

The challenge in measuring UHI bias is relating local temperature change to a corresponding change in population or urbanization, rather than to a static classification variable such as rural or urban. Spencer *et al.* (2025) used newly available historical population archives to undertake such an analysis and found evidence of significant UHI bias in U.S. summertime temperature data.

In summary, while there is clearly warming in the land record, there is also evidence that it is biased upward by patterns of urbanization and that these biases have not been completely removed by the data processing algorithms used to produce climate data sets.

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PART II: CLIMATE RESPONSE TO CO_2 EMISSIONS

4 CLIMATE SENSITIVITY TO CO_2 FORCING

Chapter Summary

There is growing recognition that climate models are not fit for the purpose of determining the Equilibrium Climate Sensitivity (ECS) of the climate to increasing CO_2. The IPCC has turned to data-driven approaches including historical data and paleoclimate reconstructions, but their reliability is diminished by data inadequacies.

Data-driven ECS estimates tend to be lower than climate model-generated values. The IPCC AR6 upper bound for the likely range of ECS is 4.0°C, lower than the AR5 value of 4.5°C. This lowering of the upper bound seems well justified by paleoclimatic data. The IPCC AR6 lower bound for the likely range of ECS is 2.5°C, substantially higher than the AR5 value of 1.5°C. This raising of the lower bound is less justified; evidence since the AR6 finds the lower bound of the *likely* range to be around 1.8°C.

4.1 Introduction

The climate's response to increasing concentrations of CO_2 is central to the scientific debate on anthropogenic climate change, and so also to the public debate on "climate action." The simplest measure of that response is the rise in the global average surface temperature, quantified by the Equilibrium Climate Sensitivity (ECS). ECS is defined as the amount of warming expected in response to a doubling of CO_2 from its pre-industrial concentration of 280 ppm, after all climate components have had time to adjust. Some components, like temperatures in the lower atmosphere (troposphere), adjust rapidly, while others such as the deep ocean and cryosphere might take as long as centuries. A related measure, the Transient Climate Response (TCR), better describes the shorter time scales; it is defined as the amount of warming when the CO_2 concentration is doubled by rising one percent annually for 70 years.

The 1979 Charney Report for the U.S. National Academy of Sciences (National Research Council 1979) proposed that the most likely ECS was 3.0 ± 1.5°C. The IPCC repeatedly reaffirmed that range with only minor variations until its most recent AR6. AR5 termed 1.5–4.5°C as the *likely* range (66 percent probability) and stated that ECS is *extremely unlikely* (95 percent probability) to be below 1.0°C and *very unlikely* (90 percent probability) to exceed 6.5°C.

The uncertainty in ECS has remained stubbornly wide, despite many individual studies that claimed to narrow it (Hausfather 2023). Most recently, AR6 narrowed the *likely* range to 2.5–4.0°C and deemed the *very likely* range to be 2.0–5.0°C. This narrowing on the low end is disputed, as will be discussed below.

Uncertainties in ECS are highly consequential for policy making. As will be discussed in Chapter 11, economic models use ECS values to project the costs of CO_2 emissions. The traditional value (3.0 °C) has typically yielded modest global social costs of CO_2 emissions, sufficient to justify some policy actions, but mostly deferred to later in this century. If ECS is very high (above 4.5°C) immediate aggressive emission controls become more imperative, whereas no CO_2 emission controls are economically justifiable for ECS below 2.0°C (Dayaratna *et al.* 2016, 2020). Obtaining a precise estimate is impossible, so policy making needs to account for the uncertainty.

By itself, the equilibrium warming effect of a doubling of atmospheric CO_2 is slightly more than 1°C (Soden and Held 2006). Larger values of ECS arise from positive feedbacks that amplify the CO_2 warming. Water vapor feedback is positive: a warmer atmosphere might have more water vapor, which itself is a powerful greenhouse gas. Warmer temperatures also result in less snow and sea ice cover, allowing the

Earth to absorb more of the sun's radiation. Some simple estimates of these feedbacks increase the ECS to around 2°C (Sherwood *et al.*, 2020). Larger values of ECS are associated with positive cloud feedbacks.

Climate scientists use multiple lines of evidence to determine the Equilibrium Climate Sensitivity:

- Climate model simulations
- Historical observations
- Paleoclimatic reconstructions
- Process understanding of feedbacks

4.2 Model-based estimates of climate sensitivity

The ECS ranges given in IPCC AR4 and AR5 were obtained primarily by examining the behavior of large-scale climate models, also called General Circulation Models (GCMs). However, the IPCC changed course in its AR6 when it turned to a more direct data-driven methodology. Here we discuss some of the pitfalls of using GCMs to try to determine the Earth's climate sensitivity.

In principle, ECS is an emergent property of GCMs—that is, it is not directly parameterized or tuned, but rather emerges in the results of the simulation. Otherwise plausible GCMs and parameter selections have been discarded because of perceived conflict with an expected warming rate, or aversion to a model's climate sensitivity being outside an accepted range (Mauritsen et al. 2012). This practice was commonplace for the models used in AR4; modelers have moved away from this practice with time. However, even in a CMIP6 model, Mauritsen and Roeckner (2020) state the following regarding their Max Planck Institute (MPI) climate model (emphasis added):

> "We have documented how we tuned the MPI-ESM1.2 global climate model to match the instrumental record of warming; an endeavor which has clearly been successful. Due to the historical order of events, the choice was to do this practically by **targeting an ECS of about 3 K using cloud feedbacks**, as opposed to tuning the aerosol forcing."

In other words, the MPI modelers chose an ECS value of 3°C and then tuned the cloud parameterizations to match their intended result.

As noted, direct warming from CO_2 doubling is only about 1°C (Soden and Held 2006); further warming arises from climate feedbacks that are not explicitly resolved by the GCM but rely on parameterizations of physical processes. Higher values of ECS arise primarily from assumed positive cloud feedbacks, whereas the magnitude and even the sign of the feedbacks are very uncertain. Elements of cloud feedback include changes in the latitudinal distribution of clouds, changes in the distribution of cloud height (changes in low versus high clouds), changes to the phase of clouds (ice versus liquid), changes in cloud particle size (associated with changes in concentration and/or composition of aerosol particles), changes in the precipitation efficiency of clouds, and even changes in how clouds are distributed over the daily solar cycle (Curry and Webster, 1999). It is difficult for GCMs to simulate any of these processes correctly owing to their small scale, let alone predict how they will change in the future. Further, cloud processes modulate the magnitudes of the water vapor, lapse rate, and the surface albedo feedbacks.

ECS can be determined from climate model simulations by doubling the concentration of CO_2 and allowing several centuries for the warming to equilibrate. To avoid the need for such long simulations, "effective climate sensitivity" is commonly evaluated from a 150-year simulation in response to a sudden quadrupling of CO_2.

The spread of ECS values from the CMIP5 ensemble of climate models used in AR5 was 2.0–4.7°C; that range increased for the CMIP6 models used in AR6 to between 1.8 and 5.7°C (Chen *et al.*, 2021, Scaffeta 2021, see Figure 4.1). Far from resolving the model-based climate sensitivity the range appears to be growing. The main cause of the overall upward shift in ECS in CMIP6 relative to CMIP5 is a larger positive cloud feedback, driven by changes to the cloud parameterizations in many CMIP6 models (Zelinka *et al.*, 2020)

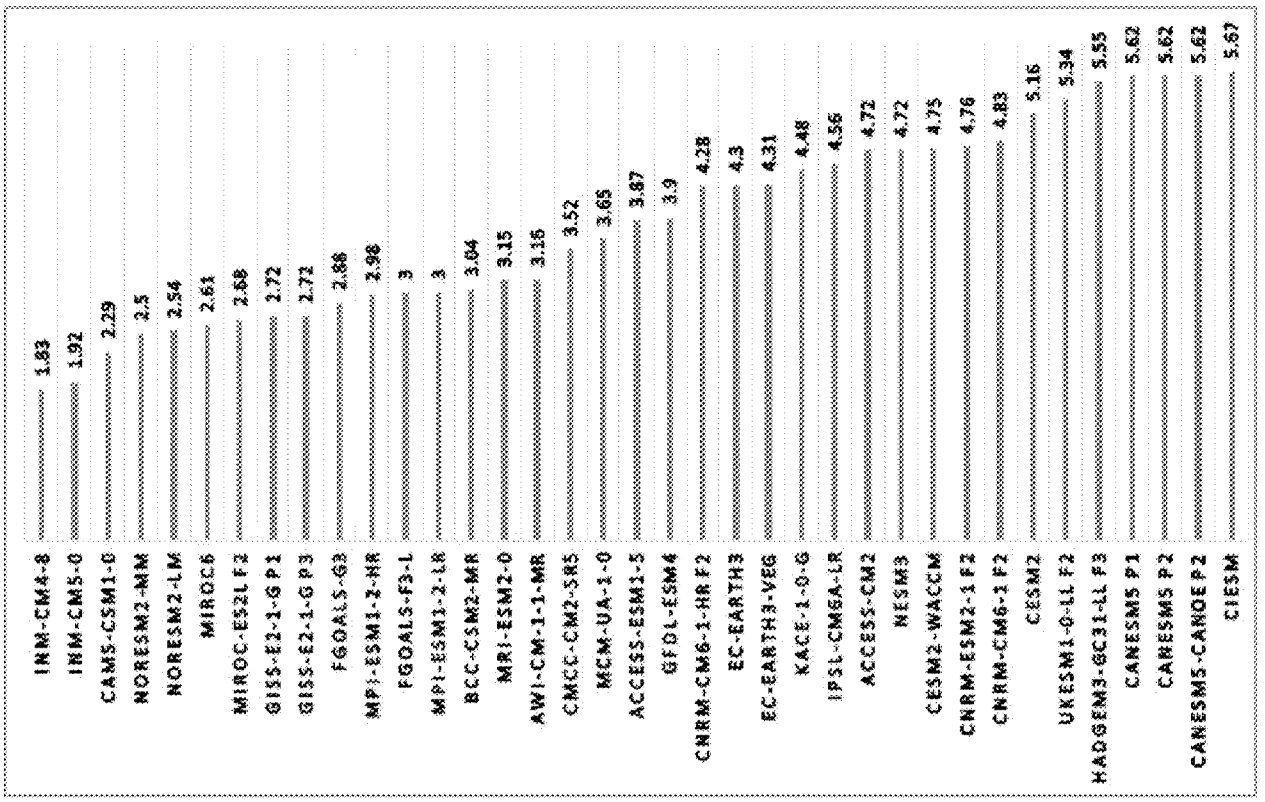

Figure 4.1 Equilibrium Climate Sensitivities in °C of 37 climate models from the CMIP6 ensemble. Identifiers for the various models appear along the horizontal axis. From (Scafetta, 2021)

Because of concerns about model tuning and the high sensitivity to cloud parameterizations, the IPCC AR6 (2021) did not rely on climate model simulations in their assessment of climate sensitivity, relying instead on data-driven methods.

4.3 Data-driven estimates of climate sensitivity

Climate sensitivity can also be estimated from instrumental records of surface temperatures and ocean heat content, combined with estimates of how climate forcings (e.g., greenhouse gases, solar, volcanoes, aerosols) have changed in the past (Otto *et al.*, 2013). Using this information, a simple empirical model called an Energy Balance Model can be employed. It requires estimating a feedback parameter whose uncertainties are highly amplified in the resulting ECS (Roe and Baker, 2007).

The accuracy of the data-driven methods depends on the quality of the input data. Assumptions are needed about ocean heat storage, and good data is only available for recent decades. The greatest source of uncertainty is the amount and composition of aerosol particles and their interactions with cloud radiative properties (the so-called aerosol indirect effect; see Figures 3.1.1, 3.1.2). Climate models exhibit warming in response to GHGs but cooling in response to aerosols (Schwartz *et al.*, 2007). Observed 20th century warming can be shown to be consistent either with low ECS and low aerosol cooling, or high ECS and high aerosol cooling. Since fossil fuel use adds both GHGs and aerosols to the atmosphere, both effects need to be estimated to isolate the warming effect of CO_2.

Paleoclimate proxies are also used to evaluate the sensitivity of past climates by comparing paleoclimate changes in the Earth's temperatures to estimates of changes in forcings. The two most informative periods are the last glacial maximum (around 20,000 years ago), which was about 3–7°C colder than today, and a mid-Pliocene period (roughly three million years ago), which was 1–3°C warmer than today. The limits on cooling during the last glacial maximum give the best single evidence that high values of climate sensitivity are unlikely. However, paleoclimate estimates are associated with very large uncertainties in the estimated temperatures and forcings. Further, estimates of climate sensitivity based on past climate states might not be applicable to the current state of the climate system.

A recurring theme in the climate literature is that ECS estimates based on historical data are smaller than ECS estimates inferred from climate models (Sherwood and Forest 2024). About 15 estimates based on historical data appeared in the peer-reviewed literature between 2012 and 2024 yielding ECS best estimates between 1.0°C and 2.5°C, although critics have questioned some of the methods and the data quality. For AR6, the IPCC placed primary weight on the results of Sherwood *et al.* (2020) that combined historical data and paleoclimate proxies with the process-based approach and yielded a best estimate of 3.1°C with a *likely* range of 2.6-3.9°C. Lewis (2022) raised a number of concerns about this result, including methodological errors, outdated input values, and use of subjective Bayesian priors in the analysis. Lewis' analysis found that climate sensitivity is estimated to be much lower and better constrained than in the Sherwood *et al.* analysis – median 2.2°C (1.8–2.7°C in the 17–83 percent *likely* range, and 1.6–3.2°C in the 5–95 percent *very likely* range). The IPCC AR6 estimated only a 5 percent probability that ECS was below 2.3°C, whereas Lewis estimated it to be over 50 percent. The most recent publications on the debate between Sherwood *et al.* and Lewis further defend their respective positions: Sherwood and Foster (2024) and Lewis (2025).

An argument emphasized in AR6 is that data-driven ECS estimates might understate the future warming response to GHGs because of a so-called "pattern effect" (Forster *et al.*, 2021). The tropical Pacific is believed to strongly influence the overall efficiency with which the Earth radiates heat to space, but some regions remove heat more efficiently than others. If the west-to-east temperature gradient in the tropical Pacific is weakened in a warming climate, warming would concentrate where heat is less efficiently removed, raising ECS.

Most climate models simulate that rising GHGs will weaken the west-east temperature gradient, which led the IPCC in AR6 to conclude that data-driven ECS estimates understated the *future* ECS value. However, Seager *et al.* (2019) pointed out that, contrary to models, the west-east temperature gradient has been strengthening over time. They further argued that the mechanism predicting otherwise in climate models was based on a faulty characterization of oceanic dynamics and there is no reason to expect the gradient to weaken. A similar argument was recently made by Lee *et al.* (2024), who concluded that "the trajectory of the observed trend reflects the response to increasing GHG loading in the atmosphere"; in other words, GHG warming should lead to a future strengthening rather than a weakening of the temperature gradient. Increased efficiency of atmospheric cooling implies, if anything, that the future ECS in a warming climate might be *lower* than current estimates.

4.4 Transient Climate Response

The Transient Climate Response (TCR) provides a more useful observational constraint on climate sensitivity. TCR is the global temperature increase that results when CO_2 is increased at an annual rate of 1 percent over a period of 70 years (*i.e.*, doubled gradually). Relative to the ECS, observationally determined values of TCR avoid the problems of uncertainties in ocean heat uptake and the fuzzy boundary in defining equilibrium arising from a range of timescales for the longer-term feedback processes (*e.g.*, ice sheets). TCR is more generally related to peak warming and better constrained by historical warming, than ECS. IPCC AR6 judged the *very likely* range of TCR to be 1.2–2.4°C. In contrast to ECS, the upper bound of TCR is more tightly constrained. For comparison, the TCR values determined by Lewis (2023) are 1.25 to 2.0°C, showing much better agreement with AR6 values than was seen in a comparison of the ECS values.

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5 MODELS VERSUS OBSERVATIONS IN THE RECENT PAST

Chapter summary

Climate models show warming biases in many aspects of their reproduction of the past several decades. In response to estimated changes in forcing they produce too much warming at the surface (except in the models with lowest ECS), too much warming in the lower-and mid-troposphere and too much amplification of warming aloft.

Climate models also produce too much recent stratospheric cooling, invalid hemispheric albedos, too much snow loss, and too much warming in the Corn Belt. The IPCC has acknowledged some of these issues but not all.

5.1 Introduction

Climate models are the primary tool used to project future climate changes in response to increasing atmospheric levels of anthropogenic greenhouse gases. To assess the fitness of climate models for this purpose, it is reasonable to ask how well they reproduce the current climate and its variations over the past century. The box "Climate modeling" gives some detail on how climate models work.

Of great concern is the fact that, after several decades of the climate modeling enterprise involving approximately three dozen models operated by research centers around the world, the range of future warming they produce in response to a hypothetical doubling of atmospheric CO_2 extends over a factor of three, as we discussed in the previous chapter. This range of disagreement among models has not decreased for decades.

Problems with climate models are not just in their disagreement over the future, but also in their ability to replicate the recent past. Here we review some of the most important metrics of climate model accuracy: ability to reproduce historical surface, tropospheric and stratospheric temperature trends; ability to reproduce the vertical warming profile; and ability to reproduce other climate features such as snowfall. In all cases a persistent finding is that models on average err on the side of too much warming in response to estimated historical forcings.

BOX: Climate modeling

Most climate models, except for the simplest ones, represent Earth's land surface using a grid of squares on the order of 100 km wide. To simulate the atmosphere, typically 30 or more grid boxes are stacked above these squares. The ocean is modeled using a similar but finer grid, resulting in tens of millions of grid boxes for the atmosphere and oceans.

The computer models, based on physical laws, calculate how air, water, and energy move between grid boxes over time. The time step can be as small as 10 minutes, and repeating this process millions of times allows the simulation of climate over centuries. Running these models, even on the most powerful supercomputers, can take months. Comparing simulation results with historical climate data helps assess the accuracy of a model, while projections into the future estimate climate changes under assumed human and natural influences.

Despite sounding straightforward, climate modeling is highly complex. Many critical processes occur at scales smaller than the grid size. For instance, the flows of sunlight and heat in the atmosphere depend strongly on cloud cover. Since tracking individual clouds is impractical, researchers must make "subgrid" assumptions about the distribution of clouds in each grid box. Snow and ice cover, which affects how much sunlight is reflected or absorbed by the surface, is another subgrid factor.

Each subgrid assumption requires numerical parameters, which must be carefully set. Modelers initially estimate these parameters based on physics and observed climate patterns, then run the model. Because early results often diverge significantly from real-world observations, they "tune" these parameters to better match observed climate features. Different modeling teams use distinct assumptions and tuning strategies, leading to varied outcomes. Tuning is a necessary but delicate aspect of climate modeling, as it is for any complex system. Poor tuning can result in inaccurate simulations, while excessive tuning risks artificially steering results toward predetermined conclusions.

The spread of model representations of the current climate is very wide. One of the most basic indicators—Earth's average surface temperature—varies by about 3°C across CMIP6 models prior to 1880 (Figure 5.1), narrows slightly until 2040 then diverges to over 4 °C. For comparison 20th century warming was only about 1.0°C. This variation suggests substantial differences among models' physical processes.

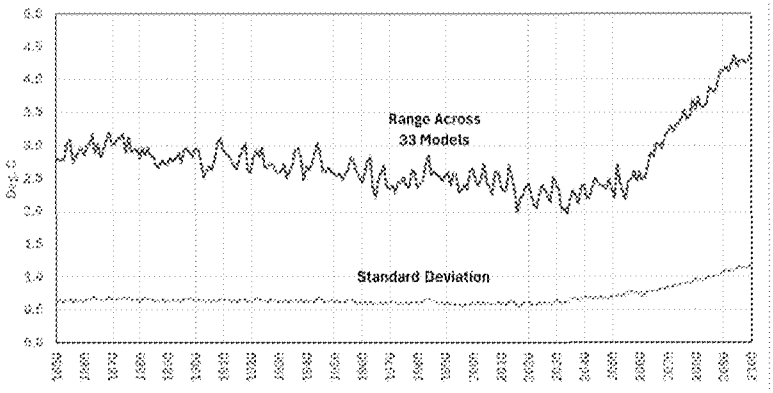

Figure 5.1 CMIP6 Average surface temperature range across 33 models and standard deviation using SSP5-85 scenario. Data from KNMI Climate Explorer website at https://climexp.knmi.nl/start.cgi.

Beyond the models' ability to reproduce features of today's climate, the critical issue for society is how well they predict responses to subtle human influences, such as greenhouse gas emissions, aerosol cooling, and land-use changes. The most crucial aspect that models must capture correctly is "feedbacks." These occur when climate changes either amplify or suppress further warming. In general, the modeled net effect of all feedbacks doubles or triples the direct warming impact of CO_2.

5.2 Surface warming

A straightforward test of a climate model's validity is its ability to reproduce historical warming in response to known past changes in climate drivers such as greenhouse gases. Figure 5.2 is reproduced from Scaffeta (2023), that groups the latest-generation (CMIP6) climate models into low ECS (1.5 to 3.0 degrees C), medium ECS (3.0 to 4.5 degrees C) and high ECS (4.5 to 6.0 degrees C), and compares their post-1980 global average temperature simulation ranges to those of three surface temperature records and one satellite-based lower troposphere temperature data product.

The leftmost column shows that the low-ECS models track the post-1980 historical warming record reasonably well, but the middle and right columns show that the medium- and high-ECS models conspicuously over-predict the warming.

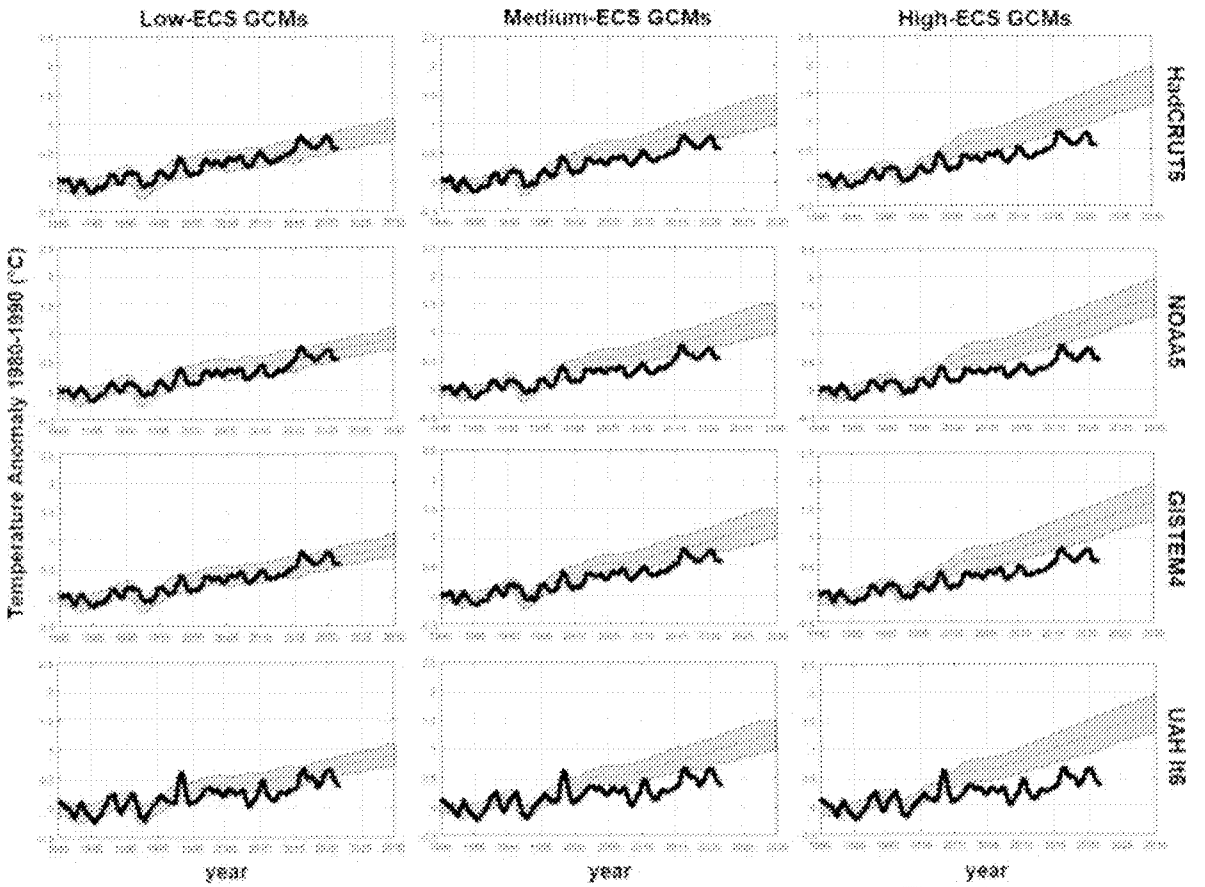

Figure 5.2: Model-Observational comparisons for Earth's surface warming. The columns correspond to model groups showing low-ECS to high-ECS, while the rows correspond to widely-used observed temperature records, the first three showing surface averages and the fourth showing the lower troposphere average. In each panel the yellow area denotes the mean and range (± one standard deviation) of climate model simulations for that group. The thick black line shows the observed annual average temperature in the indicated source. Source: Scafetta (2023) Fig.2.

Spencer (2024) has also provided a useful summary of the Model-Observation mismatch by comparing trends in surface temperature data products with those in individual climate models, as summarized in Figure 5.3; most climate models show substantially more warming than the observations since 1979.

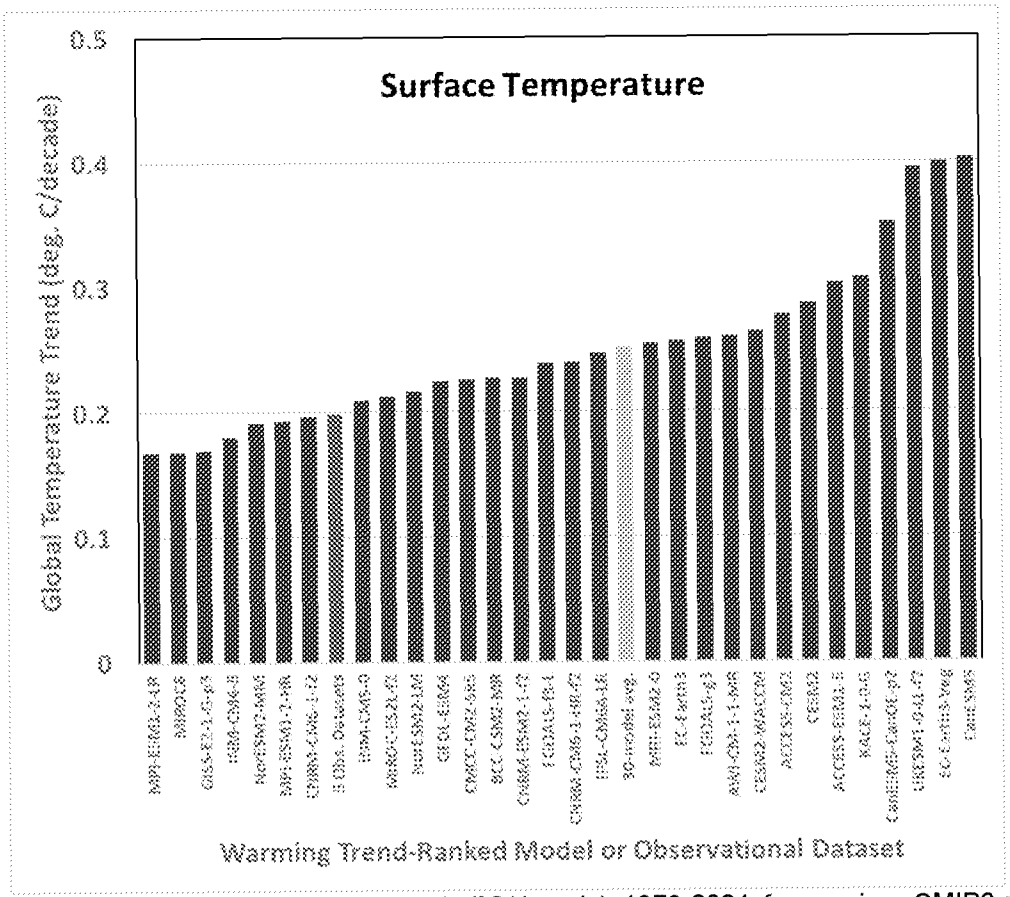

Figure 5.3 Global surface air temperature trends (°C/decade), 1979-2024, from various CMIP6 climate models (red, 30-model average in orange); and the average of three thermometer datasets (HadCRUT5, NOAA Global Temp, and Berkeley 1 deg.) and two reanalysis datasets (ERA5 and NCEP/NCAR R1) in blue. Data source: https://climexp.knmi.nl/start.cgi.

5.3 Tropospheric warming

It has long been known that climate models on average overstate warming in the tropical troposphere. This region is an important test of climate models since this is where the signal of anthropogenic greenhouse warming emerges first and most strongly. Biases in tropospheric trends indicate model flaws in heat transfer processes that carry over to surface warming biases.

The discrepancy was flagged as a serious inconsistency in the first U.S. Climate Change Science Program report (Karl *et al.* 2006) and has been mentioned in every IPCC report since, but the discrepancy has gotten worse over time, and the bias is now global. McKitrick and Christy (2020) compared tropospheric warming trends in CMIP6 climate models to observed trends from satellites, weather balloons and reanalysis systems. Every model overpredicted the average observed warming trend over 1979-2014 in both Lower- and Mid-Troposphere layers, both globally and in the tropics. In most individual models the bias was statistically significant and on average across models it was highly significant.

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Figure 5.4 presents the comparisons with data updated to 2024 (McKitrick and Christy 2025). The recent warm years moved the observed trend up slightly and widened the trend confidence intervals but the overall pattern remains the same: model bias is towards too much warming, in most cases the difference is statistically significant and on average the bias is statistically highly significant. McKitrick and Christy (2020) also showed that the bias is larger in high-ECS models, but even the models with lower average ECS predict too much warming. If future climate models were to realistically represent global tropospheric warming, they would likely be less sensitive than even the low-ECS members of the CMIP6 ensemble.

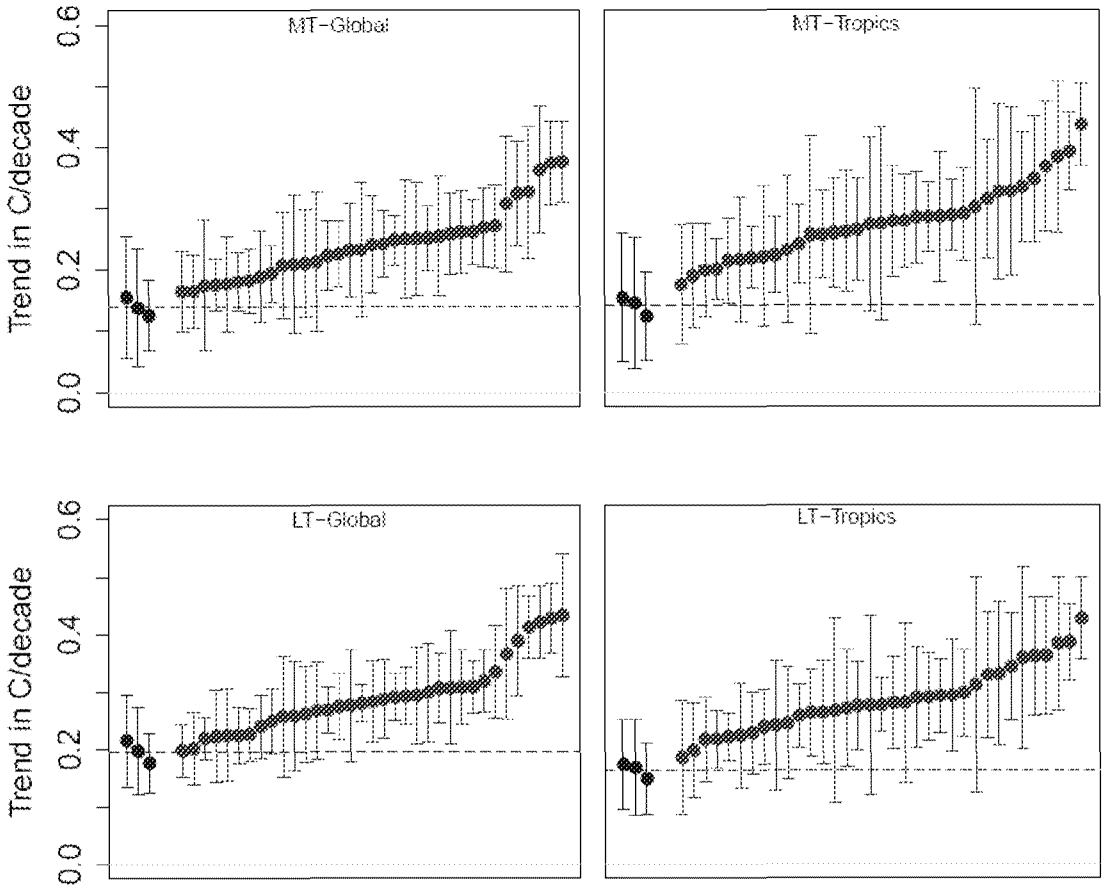

Figure 5.4: Observed versus CMIP6 modeled warming trends (°C/decade 1979-2024) in the global and tropical lower (LT) and mid-troposphere (MT). Uses methodology of McKitrick and Christy (2020) on data updated from 2014 to 2024. Blue dots: warming trends with 95 percent confidence intervals for 3 data products (radiosondes, reanalysis, and satellites). Blue dashed line: warming trend average for 3 observed series. Red dots: modeled warming trends with 95 percent confidence intervals in 35 models arranged lowest to highest.

As mentioned previously, the IPCC has long acknowledged the model-observation mismatch. For example, AR6 pp. 443-444 offers this on the tropical troposphere (it does not address the global comparison):

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> Several studies since AR5 have continued to demonstrate an inconsistency between simulated and observed temperature trends in the tropical troposphere, with models simulating more warming than observations (Mitchell *et al.*, 2013, 2020; Santer *et al.*, 2017a, b; McKitrick and Christy, 2018; Po-Chedley *et al.*, 2021)… Over the 1979–2014 period, models are more consistent with observations in the lower troposphere, and least consistent in the upper troposphere around 200 hPa, where biases exceed 0.1°C per decade. Several studies using CMIP6 models suggest that differences in climate sensitivity may be an important factor contributing to the discrepancy between the simulated and observed tropospheric temperature trends (McKitrick and Christy, 2020; Po-Chedley *et al.*, 2021), though it is difficult to deconvolve the influence of climate sensitivity, changes in aerosol forcing and internal variability in contributing to tropospheric warming biases (Po-Chedley *et al.*, 2021). Another study found that the absence of a hypothesized negative tropical cloud feedback could explain half of the upper troposphere warming bias in one model (Mauritsen and Stevens, 2015).
>
> … In summary, studies continue to find that CMIP5 and CMIP6 model simulations warm more than observations in the tropical mid- and upper-troposphere over the 1979–2014 period (Mitchell *et al.*, 2013, 2020; Santer *et al.*, 2017a, b; Suárez-Gutiérrez *et al.*, 2017; McKitrick and Christy, 2018), and that overestimated surface warming is partially responsible (Mitchell *et al.*, 2013; Po-Chedley *et al.*, 2021). …. Hence, we assess with *medium confidence* that CMIP5 and CMIP6 models continue to overestimate observed warming in the upper tropical troposphere over the 1979–2014 period by at least 0.1°C per decade,

Notably, despite the accumulation of evidence of excess model warming the IPCC assigns only *medium confidence* to the existence of a warming bias.

5.4 Vertical temperature profile mismatch

Another important model-observational discrepancy is the excess amplification with altitude found in climate models. The comparison was in the IPCC AR5 Chapter 10, although only in the online supplement (Figure 10.SM.1) and only in a figure whose formatting obscured the point. Figure 10.SM.1 is not referenced in the main IPCC report nor in any summary so readers would not have been aware of it. Although not apparent at first glance, it shows that the 1979-2010 warming in the lower troposphere is so small as to be consistent with no GHG forcing at all and is inconsistent with the model runs that do have GHG forcing. In Figure 5.6 we adapt IPCC AR5 Figure 10.SM.1 to draw out this critical point.

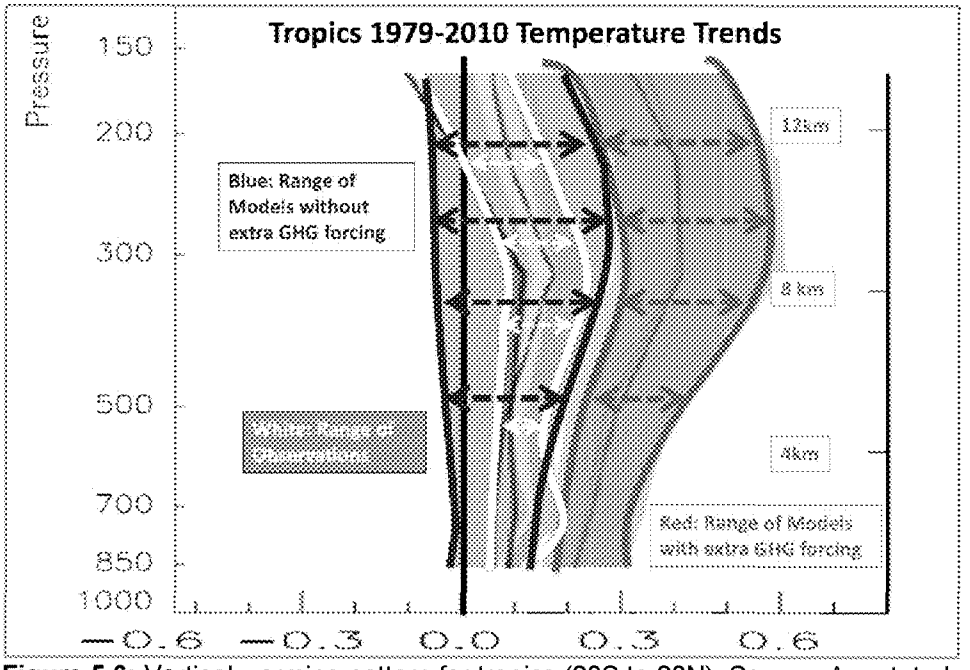

Figure 5.6: Vertical warming pattern for tropics (20S to 20N). Source: Annotated version of IPCC AR5 Figure 10.SM.1

Figure 5.6 compares model and observational temperature trends by altitude between 20S and 20N (the tropics). In this region where the models say the warming should be strongest, the observations (shown here in white) lie within the blue "No CO_2" band and entirely outside the "with CO_2" red envelope. This means that in the entire tropical atmospheric column from the surface to the base of the stratosphere, observed warming trends are so small as to be consistent with the output of models that have no anthropogenic CO_2, and inconsistent with the entire envelope of warming trends generated by models forced with increased CO_2.

A similar comparison is shown in Christy and McNider (2017), an updated version of which (covering 1979-2024) is reproduced as Figure 5.7. Modeled temperature trends exceed observations from the surface through the top of the troposphere, with observed trends below the entire model range at most pressure levels. Also shown in Figure 5.7 is the tropical tropospheric temperature (TTT) average from three satellite data products (NOAA, UAH and RSS) compared to the same layer average from climate models for 1979-2024. Again, the observed trends lie below the entire model range.

The wide range of choices made by modelers to characterize the physical processes in the models (see Box: Climate Modeling in Section 5.1 above) is seen by the large spread of trends in the middle troposphere, ±40 percent about the median (Fig. 5.7). This vividly illustrates the uncertainties in attempts to model (parameterize) a complex system involving turbulence, moist thermodynamics, and energy fluxes over the full range of the tropical atmosphere's time and space scales.

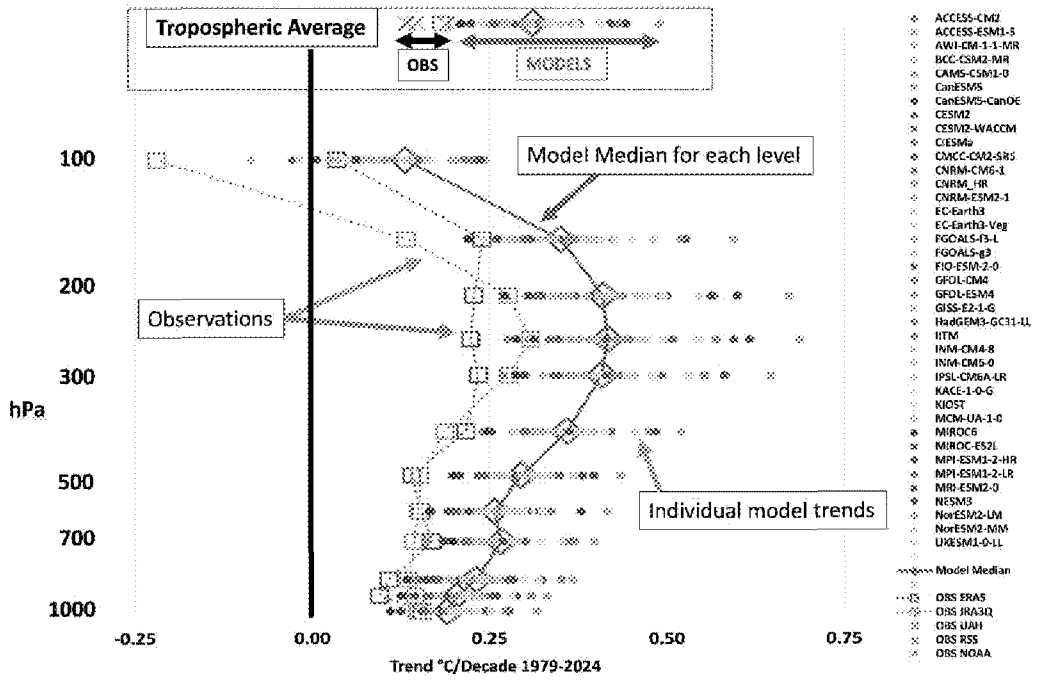

Figure 5.7: Modeled versus observed warming, tropical troposphere. Source: updated from Christy and McNider (2017) including data through 2024. Red line: model average. Green and blue lines: observational series (reanalysis).

This discrepancy has been the source of much controversy, with some arguing that even if there is very little observed warming aloft in the tropics, a "hotspot" still exists in the sense that the warming aloft is greater than at the surface (Santer et al. 2008). But there is good evidence that models also exaggerate the amplification rate. Klotzbach *et al.* (2009), showed that models project greater amplification with altitude than is observed. This result was subsequently confirmed by detailed time series analysis (Vogelsang and Nawaz 2016) which found that the model-observational difference is statistically significant.

The atmosphere's temperature profile is a case where models are not merely uncertain but also show a common warming bias relative to observations. This suggests that they misrepresent certain fundamental feedback processes.

The IPCC AR6 did not assess this issue.

5.5 Stratospheric cooling

An important element of the expected general "fingerprint" of anthropogenic climate change is simultaneous warming of the troposphere and cooling of the stratosphere. AR6 acknowledged that cooling had been observed but only until the year 2000. The stratosphere has shown some warming since, contrary to model projections.

AR6 WG1 Ch 2 pp. 327-9 states:

> Temperatures averaged through the full lower stratosphere (roughly 10–25 km) have decreased over 1980–2019 in all data products, with the bulk of the decrease prior to 2000. The decrease holds even if the influence of the El Chichon (1982) and Pinatubo (1991) volcanic eruptions on the trend,

> found by Steiner *et al.* (2020a) to have increased the 1979–2018 cooling trend by 0.06°C per decade, is removed. Most datasets show no significant or only marginally significant trends over 2000–2019, and the results of Philipona *et al.* (2018) show weak increases over 2000–2015 in the very lowermost stratosphere sampled by radiosondes….
>
> It is virtually certain that the lower stratosphere has cooled since the mid-20th century. However, most datasets show that lower stratospheric temperatures have stabilized since the mid-1990s with no significant change over the last 20 years. It is likely that middle and upper stratospheric temperatures have decreased since 1980, but there is low confidence in the magnitude.

The cited source, Philipona *et al.* (2018), in an article entitled "Radiosondes Show That After Decades of Cooling, the Lower Stratosphere Is Now Warming", stated:

> In response to continued greenhouse gas increases and stratospheric ozone depletion, climate models project continued tropospheric warming and stratospheric cooling over the coming decades. Global average satellite observations of lower stratospheric temperatures exhibit no significant trends since the turn of the century. In contrast, an analysis of vertically resolved radiosonde measurements from 60 stations shows an increase of lower stratospheric temperature since the turn of the century at altitudes between 15 and 30 km and over most continents. Trend estimates are somewhat sensitive to homogeneity assessment choices, but all investigated radiosonde data sets suggest a change from late twentieth century cooling to early 21st century warming in the lower stratosphere.

A combination of tropospheric warming and stratospheric cooling is a commonly cited "fingerprint" of anthropogenic warming. Stratospheric warming since 2000 coincides with continued surface and tropospheric warming, a pattern that is not found in climate model simulations and is not apparently consistent with the anthropogenic fingerprint.

5.6 Snow cover mismatch

Data compiled by the Rutgers University Snow Lab show that Northern Hemisphere winter snow cover is not decreasing (Figure 5.8); if anything, it shows an increasing trend.

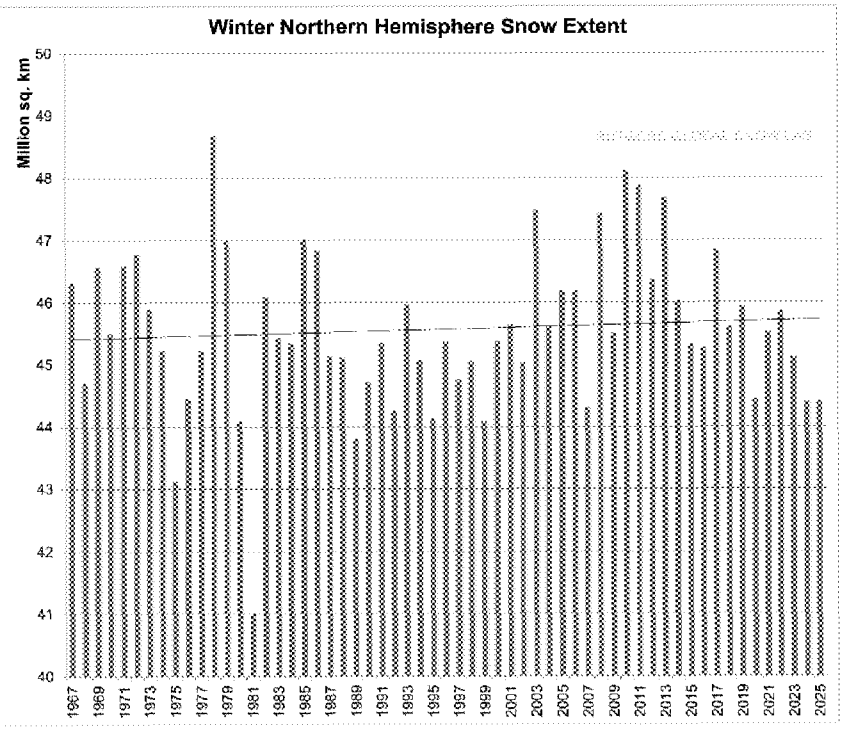

Figure 5.8: Northern Hemisphere Winter Snow extent.
Source: https://climate.rutgers.edu/snowcover/chart_seasonal.php?ui_set=nhland&ui_season=1
(accessed May 27, 2025)

Yet models project declining Northern Hemisphere snow cover in a warming climate, as described by Connolly *et al.* (2019).

> The climate models were found to poorly explain the observed trends [in Northern Hemisphere snow cover]. While the models suggest snow cover should have steadily decreased for all four seasons, only spring and summer exhibited a long-term decrease, and the pattern of the observed decreases for these seasons was quite different from the modelled predictions. Moreover, the observed trends for autumn and winter suggest a long-term increase, although these trends were not statistically significant.

AR6 largely confines its discussion of changing Northern Hemisphere snow cover extent (SCE) to the Spring season, for which models and observations agree on a downward trend. Regarding Winter changes it remarks as follows (AR6 WGI Ch. 2 p. 344):

> Assessment of SCE trends in the NH since 1978 indicates that for the October to February period there is substantial uncertainty in trends with the sign dependent on the observational product. Analysis using the NOAA Climate Data Record shows an increase in October to February SCE (Hernández-Henríquez *et al.*, 2015; Kunkel *et al.*, 2016) while analyses based on satellite borne optical sensors (Hori *et al.*, 2017) or multi-observation products (Mudryk *et al.*, 2020) show a negative trend for all seasons.

AR6 WGI Chapter 9 (p. 1284) points out that the NOAA Climate Data Record showing increased fall and winter SCE is inconsistent with land-based observations and model-based data sets. It notes that using optical satellite imagery to infer SCE in winter is challenging due to cloud cover and decreased solar illumination in winter months. Focusing on the Pacific Coast states (CA, OR and WA) cold season mountain snowfall that melts in spring and summer provides a substantial portion of warm season water resources. A comprehensive reconstruction of snowfall for the main source regions (Cascades and Sierra Nevada Mountains) indicates no significant trends in annual totals since the late 19th century (Christy 2022).

In summary, the up-to-date Rutgers SCE database indicates a mismatch between models and observations. Further work to reconcile conflicting trends in observational data sets is required.

5.7 Hemispheric symmetry of the planetary albedo

The planetary albedo is the fraction of incoming solar radiation reflected by the Earth back to space. It is an important element of the radiative energy balance and influences whether the planet will warm or cool over time. The planetary albedo is typically estimated at around 0.30; variations on the scale of 0.01 correspond to changes in solar forcing of about 3 W/m^2, an amount larger than current anthropogenic forcing. It has long been noted that models disagree with each other and with observations on the value of the global planetary albedo (Stephens *et al.* 2015).

An intriguing property of the Earth's albedo is that, on average, the Northern Hemisphere (NH) and Southern Hemisphere (SH) have had nearly the same albedo, at least throughout the fifty-year satellite record (Stephens *et al.*, 2015). This symmetry is surprising, because the SH has much more ocean than land. Since ocean is less reflective than land, the NH should have higher albedo. Clouds (which are highly reflective) are more common in the NH and so compensate the surface albedo imbalances of the two hemispheres. Datseris and Stephens (2021) show that this cloud compensation comes from the extra-tropical storm tracks of the SH, which are cloudier than those of the NH. While the mechanism for this hemispheric symmetry is unclear, it likely operates on large temporal and spatial scales.

The hemispheric symmetry of the albedo is a simple gross metric for climate models. Rugenstein and Hakuba (2023) defined that metric as the difference between the NH and SH annual mean albedos, expressed as Wm^{-2} of the reflected sunlight, and compiled it for the CMIP6 climate models, as shown in Figure 5.9. Most of the CMIP6 models do not reproduce the small observed asymmetry (about 0.1 Wm^{-2}) and even disagree as to which hemisphere is more reflective. Moreover, the magnitude of the asymmetry ranges up to 5 Wm^{-2} in some models, twice as large as the current anthropogenic forcing (about 2.5 Wm^{-2}).

The significance of unphysical albedo asymmetries in the climate models is not yet fully known. However, other model studies suggest that interhemispheric changes in albedo can alter poleward heat fluxes, meridional temperature gradients, storminess, and differences in hemispheric ocean heat storage. The discrepancy between models and observations further raises issues regarding cloud feedback processes and so more generally diminishes confidence in model projections of the future climate.

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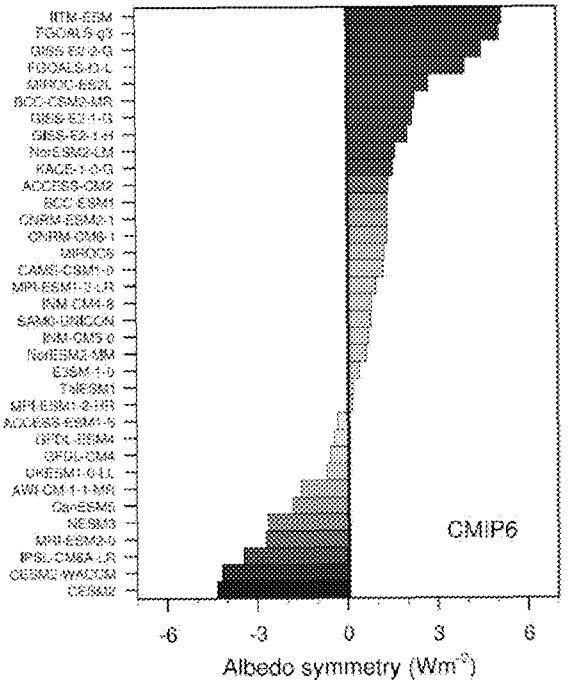

Figure 5.9. Differences in 20-year average reflectivity (albedo) between the Northern and Southern Hemispheres for CMIP6 models used in the most recent IPCC assessment (colored bars). The very small observed difference is indicated by the vertical black line. From Rugenstein and Hakuba (2023).

5.8 U.S. Corn Belt

One of the largest discrepancies between models and observations is in the U.S. Corn Belt, a region of particular importance to global food production. Figure 5.10 shows the warming trends for summertime (June, July, August) for the 12-state Corn Belt (IN, IA, IL, ND, SD, MO, MN, WI, MI, OH, KS, NE) during 1973-2022. All 36 climate models (red) warm far too rapidly compared to observations (blue).

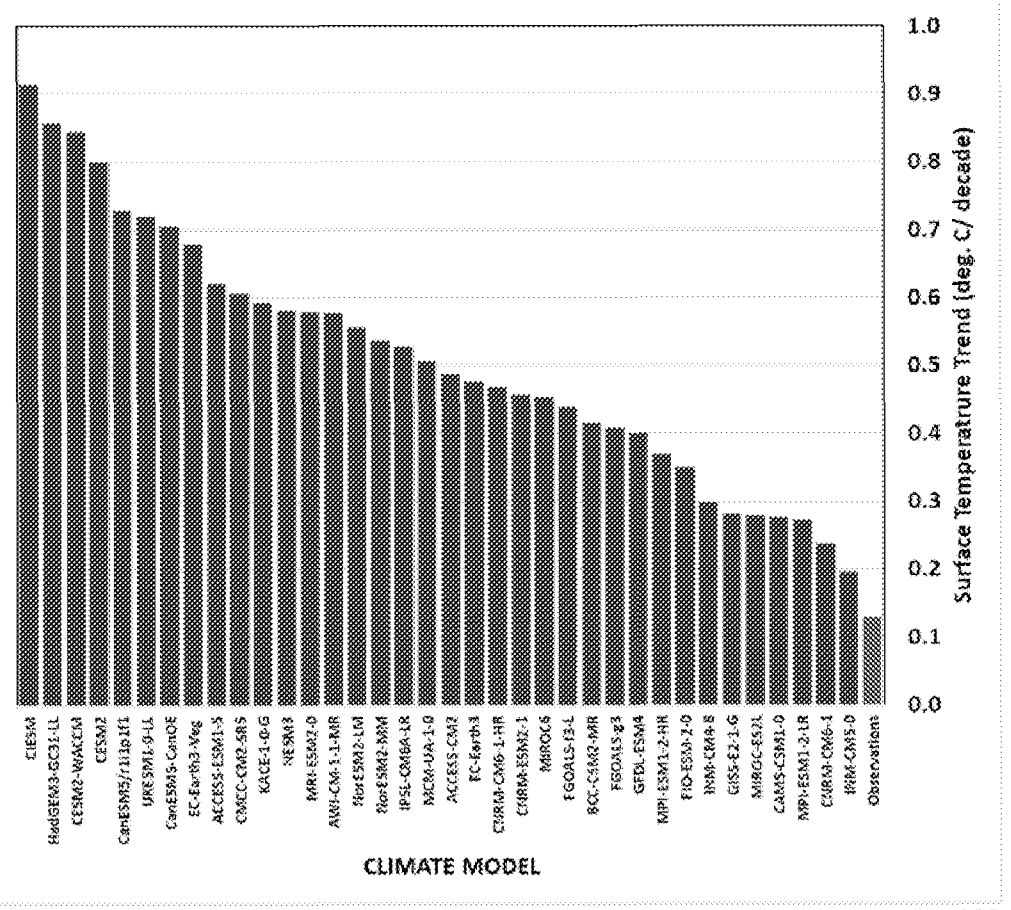

Figure 5.10: Modeled versus observed warming trends in the U.S. Corn Belt, 1973-2022.

As discussed in Chapter 9, the anticipated negative effects of increasing temperatures on U.S. corn yields have not materialized, in contrast to widely publicized studies proclaiming that theoretical future impacts are already being experienced (*e.g.*, Seager *et al.*, 2018).

The IPCC acknowledges limitations in the accuracy of regional climate model outputs. This example shows that users need to assess model projections carefully on a case-by-case basis since local biases might be sufficiently large that the models are simply not fit for purpose. As has recently been noted by two leaders of the modeling community (emphasis added)

> … for many key applications that require regional climate model output or for assessing large-scale changes from small scale processes, we believe that **the current generation of models is not fit for purpose**. (Palmer and Stevens 2019)

To summarize:

- Climate models show warming biases in many aspects of their reproduction of the past few decades.
- They produce too much warming at the surface (except in the models with lowest ECS), too much warming in the lower-and mid-troposphere and too much amplification of warming aloft
- They also produce too much stratospheric cooling, too much snow loss, and too much warming in the U.S. Corn Belt.

- The hemispheric albedo difference in individual climate models ranges widely in sign and magnitude compared to observations. The range in W/m^2 is three times larger than the direct anthropogenic forcing of CO_2.
- The IPCC has acknowledged some of these issues but not others.

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6 EXTREME WEATHER

Chapter Summary

Most types of extreme weather exhibit no statistically significant long-term trends over the available historical record. While there has been an increase in hot days in the U.S. since the 1950s, a point emphasized by AR6, numbers are still low relative to the 1920s and 1930s. Extreme convective storms, hurricanes, tornadoes, floods and droughts exhibit considerable natural variability, but long-term increases are not detected. Some increases in extreme precipitation events can be detected in some regions over short intervals but the trends do not persist over long periods and at the regional scale. Wildfires are not more common in the U.S. than they were in the 1980s. Burned area increased from the 1960s to the early 2000's, however it is low compared to the estimated natural baseline level. U.S. wildfire activity is strongly affected by forest management practices.

6.1 Introduction

High impact weather extremes, usually related to temperature, precipitation and/or high wind, can disrupt infrastructure and therefore endanger human health and wellbeing. The issue is not whether extremes occur. Rather, it is whether there are long-term (decadal scale) changes in the frequency or character of extremes ("detection"), as well as the extent to which such changes and the attendant changes in hazards are caused by anthropogenic emissions of greenhouse gases ("attribution"; e.g., AR6 Seneviratne *et al.* 2021).

It is naïve to assume that any recent extreme event is caused by human influences on the climate. Climate is about the statistical properties of weather over decades, not single events. Further, there are only about 130 years of reliable observational records that can be analyzed statistically. That brief interval does not begin to contain all the extreme events that the climate system can create on its own. Over geologic time the climate system has generated an (essentially) infinite variety of weather patterns and extremes that humans have never observed and thus are absent from the databases used to determine extreme statistics [see *Perils of short data records* below]. For that reason, attributing an extreme event unprecedented in the record requires assumptions about the magnitude of natural variations.

This chapter is concerned with detection of trends in extreme weather, while Chapter 8 considers causal attribution, with Section 8.4 specifically addressing extreme weather. If no trend is detected, then clearly there is no basis for attribution. But even where a trend is observed, attribution to human-caused warming does not necessarily follow.

This is especially true for precipitation events. The hydrological literature has long noted the phenomenon of Long-Term Persistence (LTP) in rainfall data (Hurst 1951, Cohn and Lins 2005, Markonis and Koutsoyiannis 2016). LTP has a formal mathematical definition, but it can be thought of as the presence of natural variations with strong autocorrelations that result in cycle-like behavior on long time scales. The presence of LTP requires long records to accurately estimate variability. Analysis of records that are short relative to the LTP scale will tend to underestimate variability, therefore overstating the significance of apparent trends and underestimating the likelihood of extreme events (Cohn and Lins 2005).

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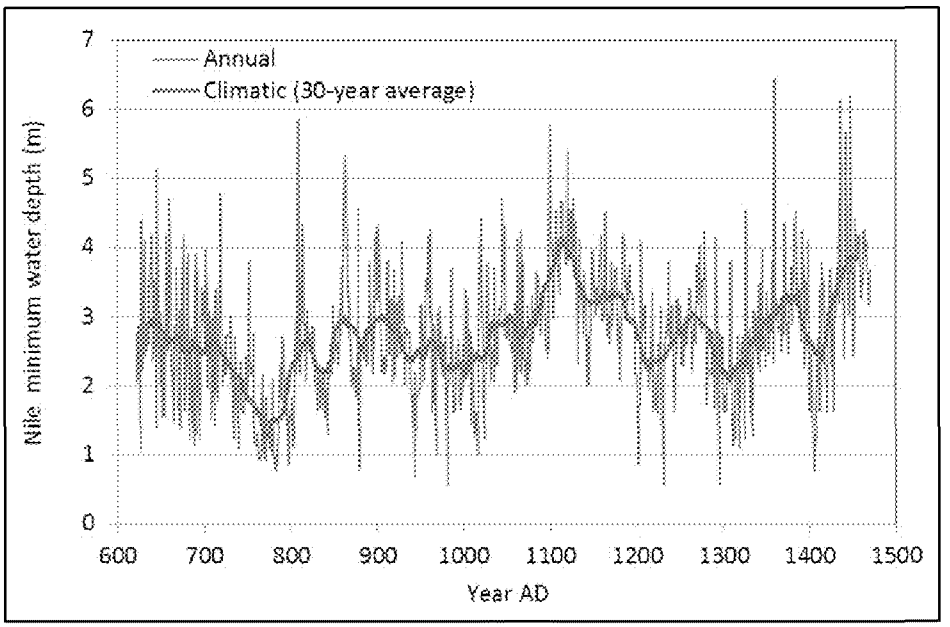

Figure 6.1.1: The annual minimum depth of the Nile River near Cairo over more than 650 years from 622 to 1284 A.D. The data, measured in meters, shows a characteristic pattern of year-to-year fluctuations around longer-term trends. Data from Koutsoyiannis (2013)

A good example of LTP is the eight-century long record of the annual minimum height of the Nile River observed at Roda Island in Cairo shown in Figure 6.1.1. The Nile River is fed by precipitation over a 4 million square mile drainage basin, an area equal to about one third of CONUS. Since human influences on the global climate were negligible before the 20th century, the century-scale variability of the thirty-year average is entirely natural; Egyptians of the seventh and eight centuries would have been incorrect to assume that the worsening drought during that time was the "new normal."

With these caveats in mind, we examine the evidence for changes in selected weather and climate extremes. A recurring theme is the wide gap between public perceptions and scientific evidence. It has become routine in media coverage, government and private sector discussions, and even in some academic literature to make generalized assertions that extreme weather of all types is getting worse due to GHGs and "climate change." Yet expert assessments typically have not drawn such sweeping conclusions and instead have emphasized the difficulty both of identifying specific trends and establishing a causal connection with anthropogenic forcing.

In the sections to follow we provide excerpts from various IPCC and NCA assessment reports denoting the sources as follows:

SREX: The IPCC Special Report on Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation (2012)

AR6: The IPCC Sixth Assessment Report Working Group 1 (2021).

NCA4: The U.S. Climate Science Special Report of the Fourth National Climate Assessment (2017) Volume I.

NCA5: The U.S. Climate Science Special Report of the Fifth National Climate Assessment (2023) Volume I.

In the excerpts. *italics* are in the original whereas **boldface** emphasis has been added.

Additionally we present updated data series from standard government sources to provide up-to-date information through 2024 wherever possible.

6.2 Hurricanes and tropical cyclones

AR6 provides the following assessment of tropical cyclones (TCs; used here as a synonym for hurricanes):

> AR6: There is *low confidence* in most reported long-term (multidecadal to centennial) trends in TC frequency or intensity-based metrics due to changes in the technology used to collect the best-track data. (IPCC, 2021 p. 1585)
>
> AR6: It is *likely* that the global proportion of major (Category 3–5) tropical cyclone occurrence has increased over the last four decades . . . There is *low confidence* in long-term (multi-decadal to centennial) trends in the frequency of all-category tropical cyclones. (IPCC, 2023 SPM p. 9)
>
> AR6: A subset of the best-track data corresponding to hurricanes that have directly impacted the United States since 1900 is considered to be reliable, and shows **no trend in the frequency of U.S. landfall events**. (IPCC 2021 p. 1585)

Since 1980, when satellite observations first fully covered the global oceans, we have confidence in the numbers of total global hurricanes and major hurricanes (Category 3 and higher). Figure 6.2.1 shows that on average, each year there are about 50 hurricanes, with about 25 reaching major hurricane status (Maue, 2025). There is substantial year-to-year and decadal variability, a weak decrease in the number of hurricanes, and a slight but insignificant increase in the number of major hurricanes. These two trends combine to create an overall increase in the proportion of major hurricanes.

Global hurricane statistics are dominated by the Northwest Pacific Ocean, which accounts for ~35 percent of total global hurricanes, whereas the Atlantic accounts for ~15 percent of global hurricanes (Colorado State University, 2025). Data in the Atlantic basin extends further back than in the other ocean basins and is most relevant to U.S. policy makers.

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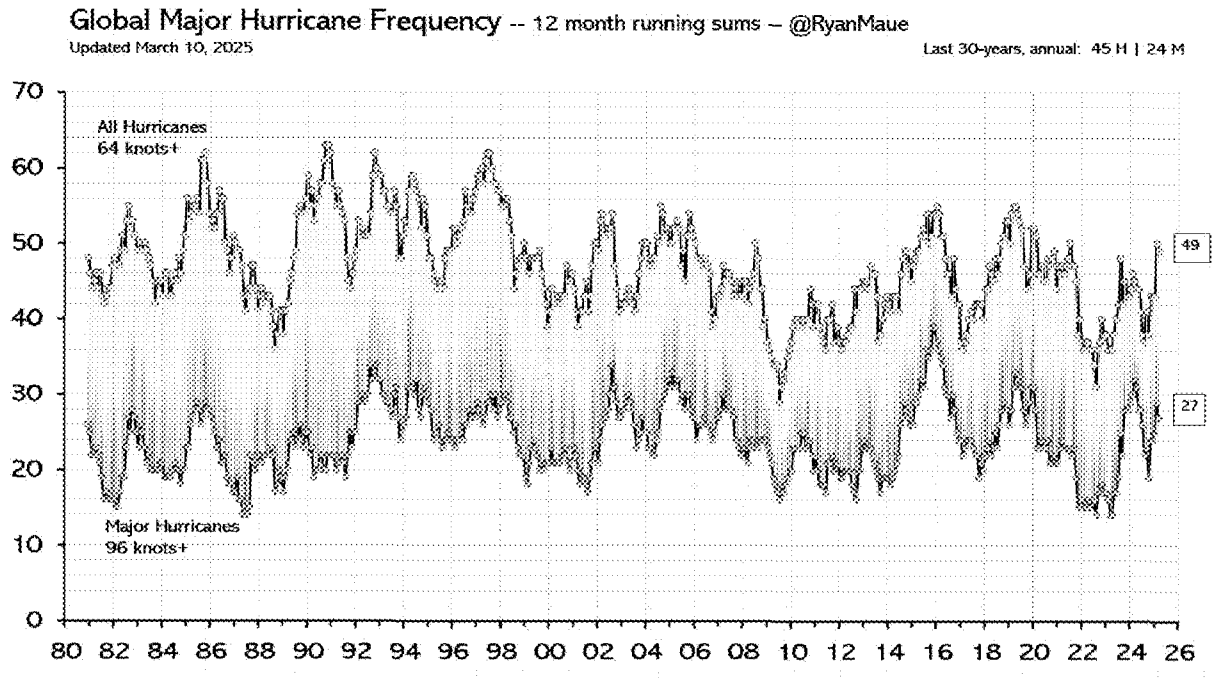

Figure 6.2.1: Global frequency of hurricanes and major hurricanes since 1980.

Figure 6.2.2 shows the frequency of Atlantic hurricanes and major hurricanes (Category 3 and higher) back to 1920. Data prior to 1965 (the onset of satellite observations in the Atlantic, shaded in blue) shows some undercounting, with data prior to 1920 showing substantial undercounting (Vecchi and Knutson, 2011). All measures of Atlantic hurricane activity show a significant increase since 1970. However, the period from 1971-1994 saw exceptionally low activity, with high activity (comparable to the past two decades, even with undercounting) also observed during the 1950's and 1960's, and even in the 1930's.

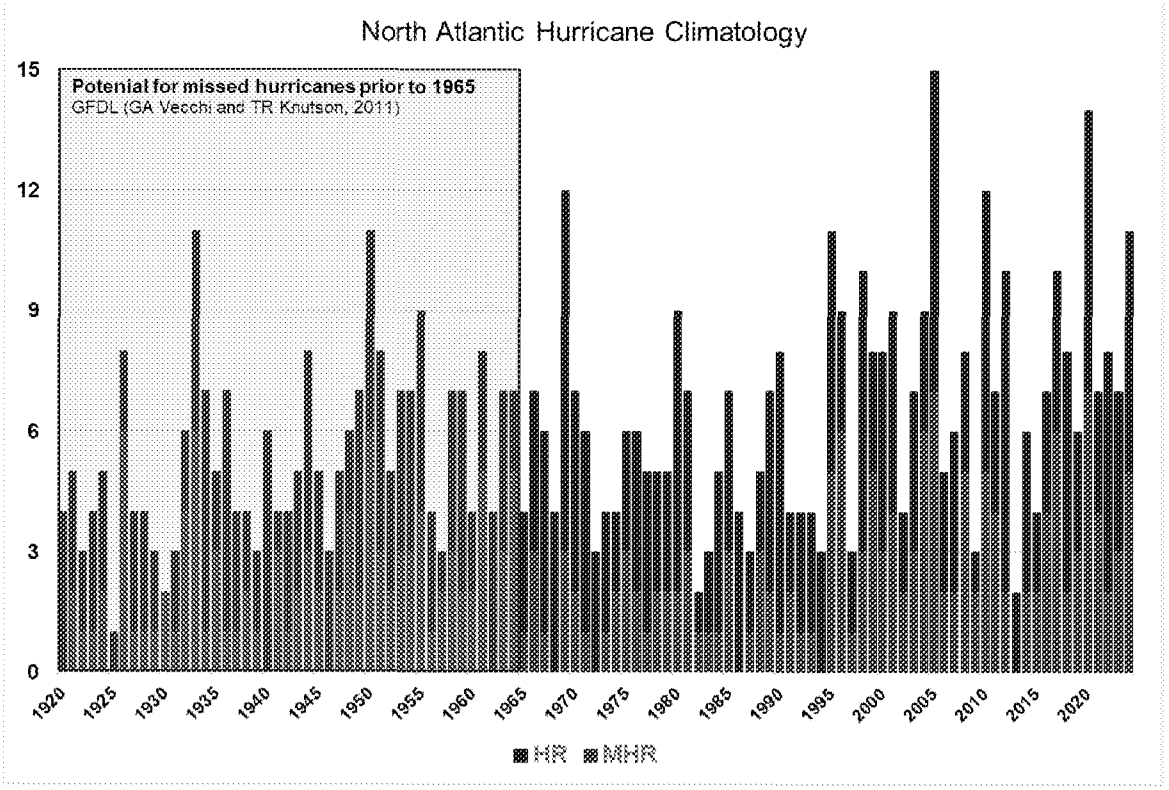

Figure 6.2.2: Atlantic frequency of hurricanes (HR) and major hurricanes (MHR) since 1920. Source National Hurricane Center (2024)

Figure 6.2.2 shows that Atlantic hurricanes vary strongly on decadal and multidecadal time scales. These variations are associated primarily with the Atlantic Multidecadal Oscillation (AMO), which is manifest in basin-wide sea surface temperature and sea level pressure fluctuations connected to large scale ocean circulation patterns. The AMO was in its warm phase during 1926-1970 and 1995-present, but in its cool phase during 1971-1994. It has its greatest impact on the number of major hurricanes (Category 3+), identified by Goldenberg *et al.* (2001) as associated with above normal SSTs and decreased vertical shear in the AMO warm phase (see also Bell and Chelliah, 2006; Klotzbach *et al.*, 2018).

Klotzbach *et al.* (2018) conducted a comprehensive evaluation of the landfalling hurricane data for the Continental U.S. since 1900. Figure 6.2.3 updates their analysis through 2024. While the largest numbers of landfalling hurricanes are from 2004, 2005 and 2020, there is no statistically significant trend since 1920. Figure 6.2.3 also shows the time series for major hurricane landfalls (Category 3-5). The largest year in the record is 2005, with 4 major hurricane landfalls. However, following 2005 there were no major hurricanes striking the U.S through 2016, the longest such period since 1920.

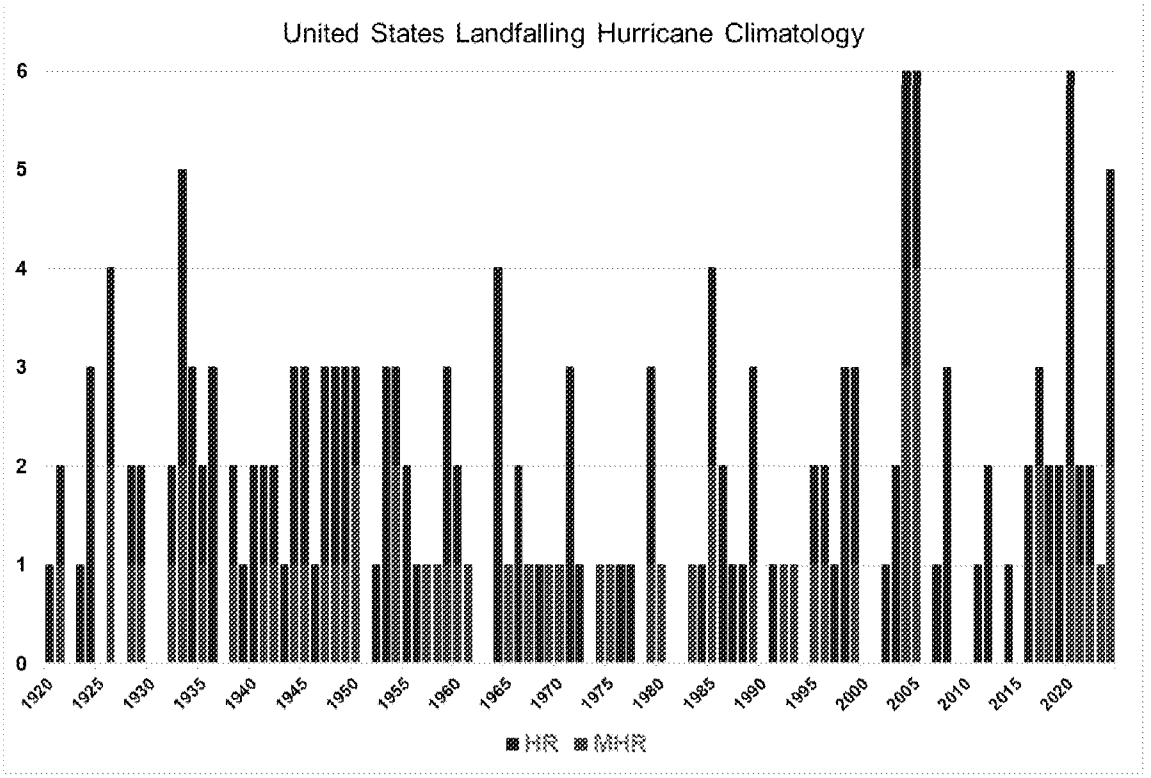

Figure 6.2.3: U.S. landfalling frequency of hurricanes (HR) and major hurricanes (MHR) since 1920. Source NOAA HRD(a) (2024)

Figure 6.2.3 shows substantial interannual to multidecadal variability in U.S. landfall activity. Klotzbach *et al.* (2018) examined how the landfall counts vary with ENSO (El Niño versus La Niña) and the warm versus cold phases of the Atlantic Multidecadal Oscillation (AMO).

Villarini *et al.* (2012) provide an analysis of U.S. hurricane landfalls back to 1878. While it is possible that some landfalls were missed in the late 19th century owing to sparsely populated regions on the Gulf Coast, it is remarkable that the highest year in the entire record is 1886, with 7 hurricane landfalls, when human influences on the climate were much smaller than they are today.

Table 6.2.1 shows the 10 strongest hurricanes (plus ties) to make U.S. landfall. Of the hurricanes that have made landfall with sustained winds greater than 150 mph, only one has occurred in the 21st century.

In summary, analyses of both global and regional variability and trends of hurricane activity provide the basis for detecting changes and understanding their causes. The relatively short historical record of hurricane activity, and the even shorter record from the satellite era, is not sufficient to assess whether recent hurricane activity is unusual relative to the background natural variability. Atlantic hurricane processes are influenced substantially by the natural modes of ocean circulation variability in the Atlantic, notably the Atlantic Multidecadal Oscillation. While it has long been hypothesized that a rising global sea surface temperature would cause an increase in hurricane intensity, identification of any significant trend in the hurricane data is hampered by a short data record and substantial natural variability.

Rank	Year	Landfall Wind (MPH)	Name
1	1935	185	"Labor Day"
2	1969	175	Camille
3	1992	165	Andrew
4	2018	160	Michael
5	1856	150	"Last Island"
5	1886	150	"Indianola"
5	1919	150	---------
5	1932	150	"Freeport"
5	2004	150	Charley
5	2020	150	Laura
5	2021	150	Ida
5	2022	150	Ian

Table 6.2.1 Strongest hurricanes to make landfall along the U.S. coast. Source (NOAA HRD(b), 2024)

6.3 Temperature extremes

The AR6 assessment focused on the period after 1950 and reported increasing trends in heatwave frequency and intensity. However, NCA4 noted that heatwave activity in the U.S. reached a peak in the 1930s (Figure 6.3.1).

> AR6: It is *virtually certain* that hot extremes (including heatwaves) have become more frequent and more intense across most land regions since the 1950s, while cold extremes (including cold waves) have become less frequent and less severe (SPM, A3.1)
>
> AR6: In North America, there is very robust evidence for a *very likely* increase in the intensity and frequency of hot extremes and decrease in the intensity and frequency of cold extremes for the whole continent, though there are substantial spatial and seasonal variations in the trends. Minimum temperatures display warming consistently across the continent, while there are more contrasting trends in the annual maximum daily temperatures in parts of the USA. (Chapter 11, p 1550)
>
> NCA4: Changes in warm extremes are more nuanced than changes in cold extremes. For instance, the warmest daily temperature of the year **increased** in some parts of the West over the past century, but there were **decreases** in almost all locations east of the Rocky Mountains. In fact, all eastern regions experienced a net **decrease**, most notably the Midwest (about 2.2°F [1.2°C]) and the Southeast (roughly 1.5°F [0.8°C]). (pp. 190-191)
>
> NCA4: Since the mid-1960s, there has been only a very slight increase in the warmest daily temperature of the year (amidst large interannual variability). Heat waves (6-day periods with a maximum temperature above the 90th percentile for 1961–1990) increased in frequency until the mid-1930s, became considerably less common through the mid-1960s, and increased in frequency again thereafter. As with warm daily temperatures, **heat wave magnitude reached a maximum in the 1930s. (pp. 190-191)**

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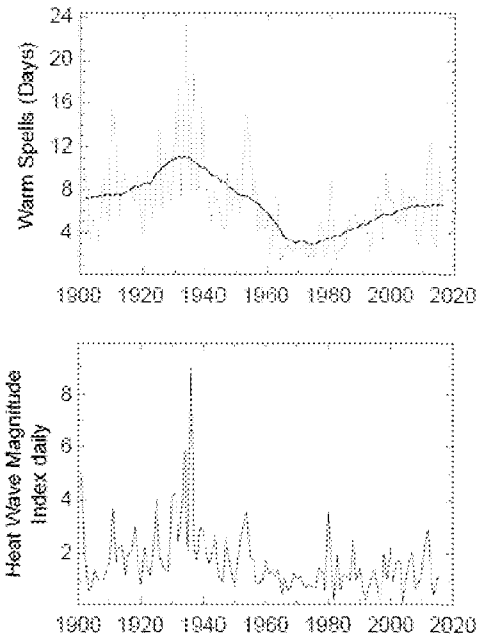

Figure 6.3.1: U.S. Heat waves since 1900. Source: NCA4 Figure 6.4

6.3.1 Temperatures in the U.S. are becoming less extreme

Daily maximum temperatures in the warm season (Tmax, May-Sep) and daily minimum temperatures in the cold season (Tmin, Dec-Mar) are available beginning in Dec 1898 (126 years). The dataset consists of 1,211 CONUS stations designated as United States Historical Climate Network or USHCN stations (see Figure 6.3.2; Quinlan *et al.* 1987, Karl *et al.* 1990). These stations were selected by NOAA as having the fewest problematic issues with gaps, station moves, and instrument changes. Where gaps still exist, nearby stations (bias-corrected) were merged so that the median volume of data available for a station is 98%. Although there are certainly errors in the dataset, including unresolved spurious warming due to UHI effects that especially bias Tmin records, this data set is sufficiently accurate for assessing trends in Tmax heat extremes.

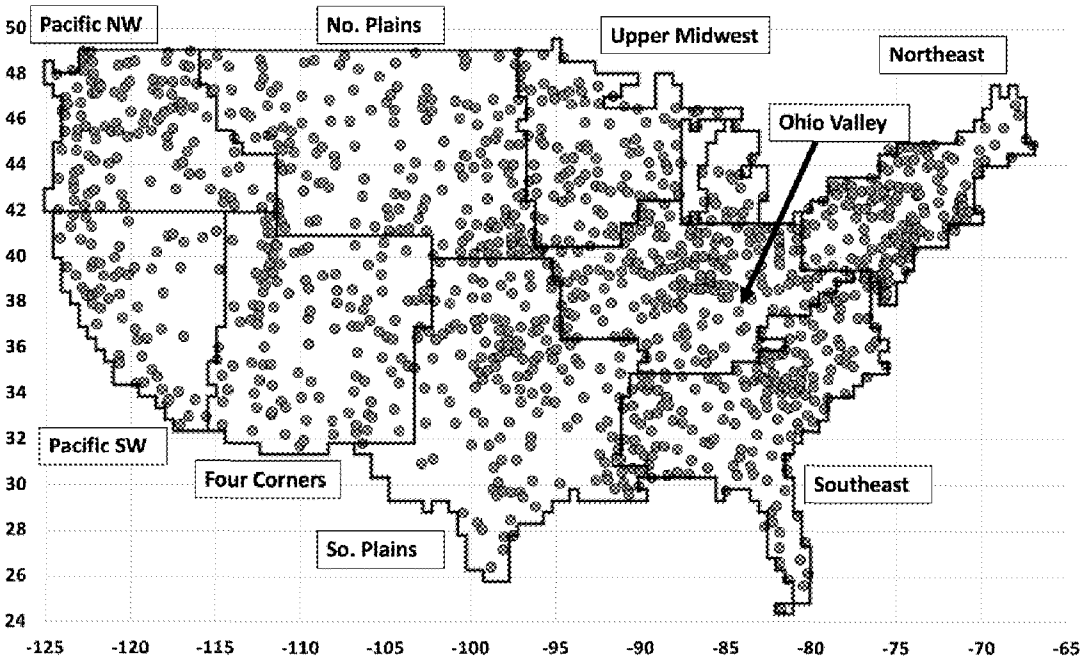

Figure 6.3.2 Locations of USHCN temperature stations. Source: USHCN.

We begin with the question of whether the occurrence of daily record high or low temperatures has changed since Dec 1898. Each warm-season has 153 days (1 May to 30 Sep) and each cold-season has 122 days (1 Dec to 31 Mar). For each station and day, we calculated the year in which the record highest (lowest) temperature occurred. With 126 years of observations, if there were no temperature trends over time, the expected number of records for Tmax would be 1.21 (=153/126) per station per year and for Tmin 0.96 (=122/126) per station per year.

Figure 6.3.3 shows the observed distribution in time of the occurrence of these extreme events. There is a common feature in many metrics of warm-season extremes in the CONUS - the exceptional heat of the 1920s and especially the 1930s, peaking in 1936. On a per-station average, 60 percent of the Tmax records and 59 percent of the Tmin records occurred in the first half of the period (1899-1961).

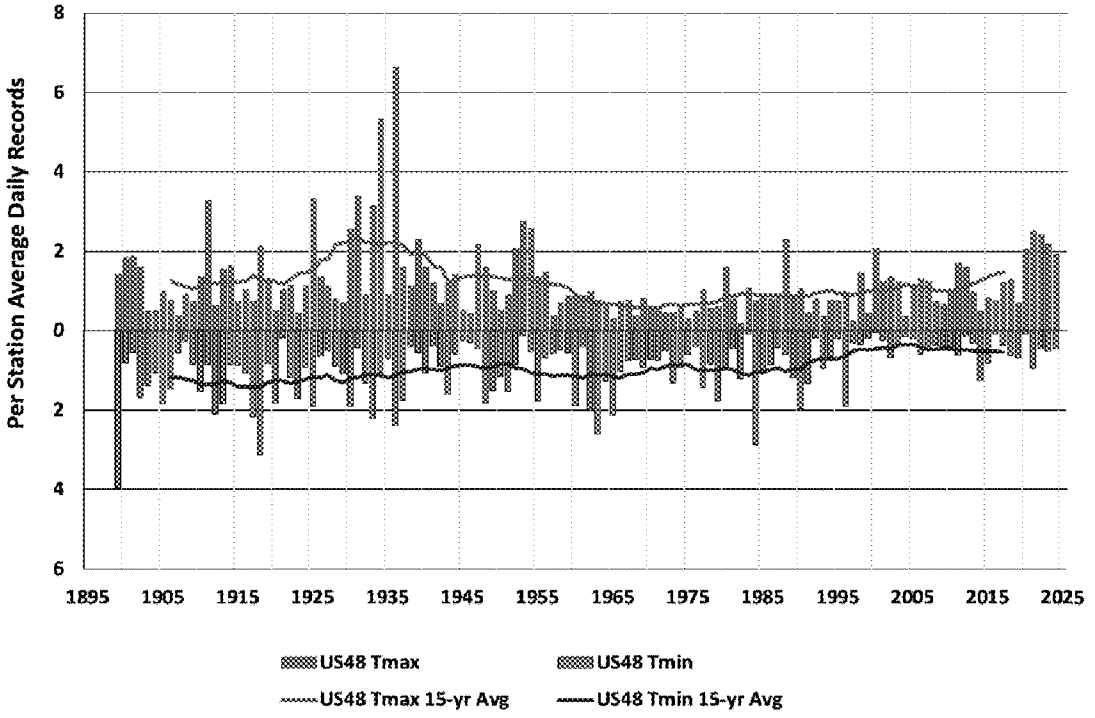

Figure 6.3.3 Number of daily record High (red) and Low (blue) temperatures for warm and cold seasons in the CONUS. The lines represent the 15-year running, centered average. Source: 1,211 USHCN stations supplemented as needed to achieve a minimum of 92 percent of observations in the 126-year period since Dec 1898. US48: contiguous U.S. states. Tmax: maximum temperature. Tmin: minimum temperature.

On the cold side, the Valentine's Day Arctic outbreak in Feb 1899 stands as the most extensive cold extreme experienced by CONUS, with 1917 in 2nd place. The frequency of cold records has declined, especially over the last quarter of the period in which only 13 percent of the extreme cold events were measured. In contrast, 25 percent of the extreme Tmax records were achieved in the last quarter, in accordance with statistical expectations. These general features have been noted in past assessments (see above, IPCC AR6, NCA4). Combining the two histories, the overall reduction in numbers of both cold and hot extremes over the past century indicates a climate less prone to extremes.

This pattern is also shown in Figure 6.3.4. For each station and for each year the hottest warm season and coldest cold-season temperatures were calculated. Then the differences between these were computed by station and geographically-averaged over all stations, thus yielding an annual measure of the expected range of local extreme temperatures for each year. Figure 6.3.4 shows the 15-year trailing average of this measure, which has clearly declined over the past century.

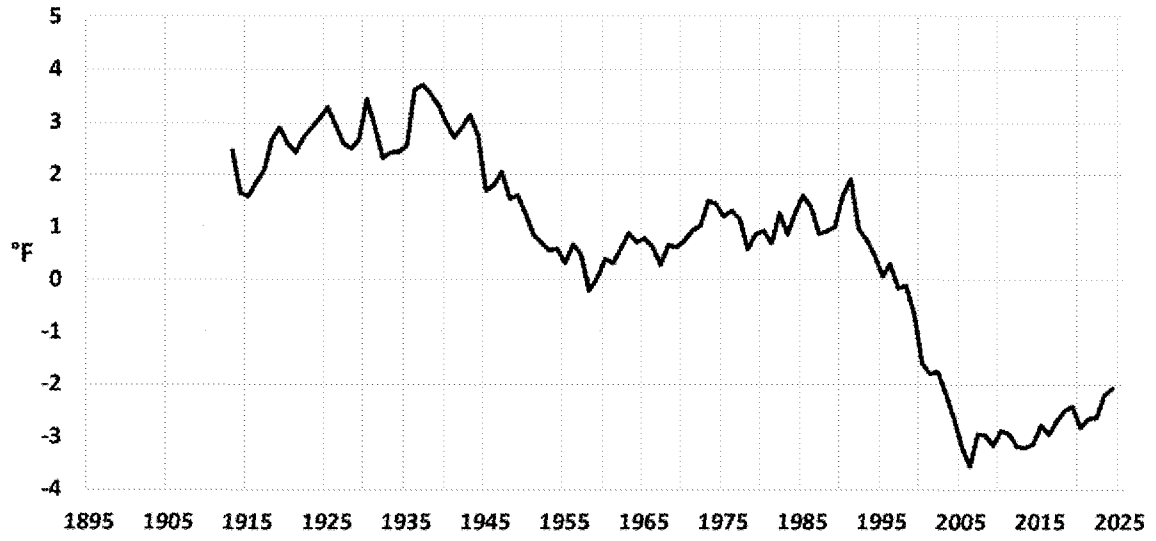

Figure 6.3.4. 15-year trailing average of the difference each year of each station's hottest warm-season Tmax and coldest cold-season Tmin relative to the long-term average. Source: Author analysis of USHCN data.

The average difference for each station between the hottest summer Tmax and coldest winter Tmin has declined by about 5°F in the past 126 years. The decline is due mostly to warmer winter Tmin, but a decline in summer Tmax is also a factor. The rise in Tmin has been strongly related to the growing presence of manufactured surfaces around the weather stations over the last 100+ years (the so-called urban heat island effect; Section 3.3 and Spencer *et al.* 2025).

In summary, while temperature extremes are regularly experienced in the U.S. and attract a great deal of media attention, long term records show the U.S. climate has become less extreme over time (milder) when measured by the range between warm season maxima and cold season minima.

6.3.2 Exceedances of a heat threshold

Under the heading of "The Risk of Temperature Extremes is Changing", the most recent U.S. National Climate Assessment report (NCA5) notes the increase in a threshold metric of number of days at or above 95°F, stating,

> The western U.S. has been particularly affected by extreme heat since the 1980s …, experiencing a larger increase in days over 95°F, as would be expected given the greater warming in that region relative to the eastern US. Several major heatwaves have affected the U.S. since 2018, including a record-shattering event in the Pacific Northwest in 2021.

Are the occurrences of 95°F days changing? In a climate as varied as that of CONUS, threshold statistics can be misleading. A region with many stations that have near 95°F Tmax average temperatures in the summer might see large swings in the metric when only small changes in average temperature occur. Elsewhere with stations that either rarely or virtually always achieve 95°F Tmax temperatures, a small change will not have much impact on the results.

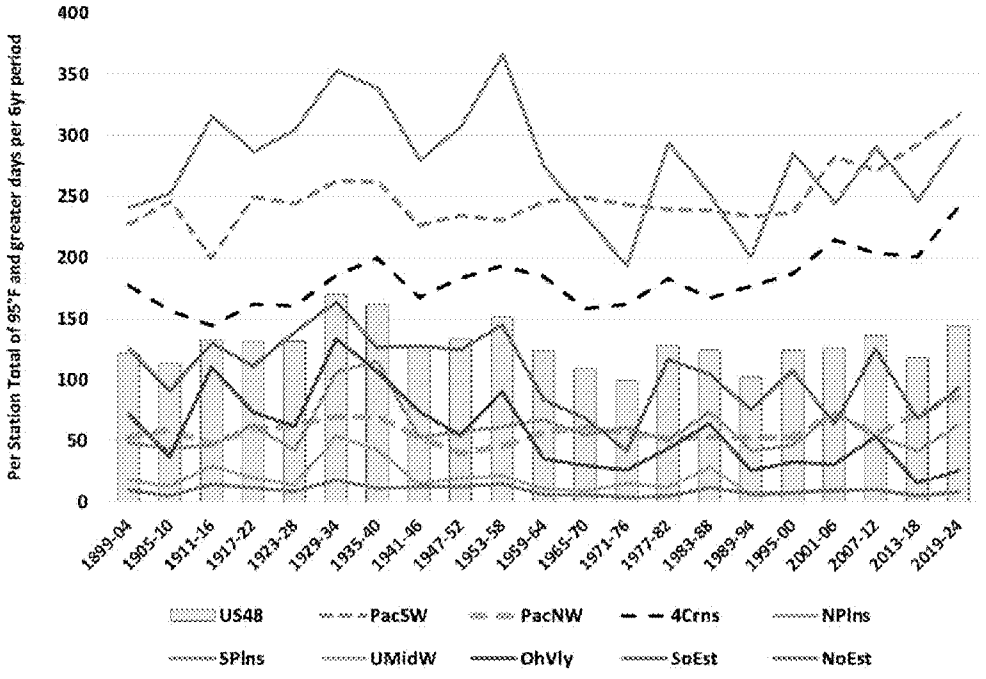

Figure 6.3.5. Total number of days ≥ 95°F in 6-yr periods, U.S. 48 (bars) and regions (lines). A 6-year period is used as this evenly divides the 126-year record. US48: contiguous U.S. states. See Figure 6.3.2 for region names. Source: Author analysis of USHCN data.

In the past 126 years, the average CONUS station experienced 129 days exceeding 95°C per 6-yr period, but the regional values range from 278 in the Southern Plains to 9 in the Northeast. Thus, such threshold analyses must be interpreted with caution. Figure 6.3.5 shows that only three of the nine regions, all in the West, have experienced upward trends in the number of 95°F or hotter days (dashed lines). The CONUS as a whole has not, and the other six regions have experienced declines.

The Pacific NW heatwave of 2021 referenced in the NCA5 quote will be examined more closely in Section 8.6.1. The evidence indicates that it was a single, unprecedented event in the record, not part of a pattern of increasing extreme heat. For example, the 5-day average tropospheric grid-point temperature anomaly over the Pacific NW during that event was +10.8 C, the most extreme Northern Hemisphere grid point summer anomaly in the 46 years from over 4 million grid values. In contrast, the global temperature anomaly during that time was virtually zero (+0.03 C, Mass *et al.* 2024).

The NCA5 heading "The Risk of Temperature Extremes is Changing" suggests pervasive positive trends are now being observed in threshold temperatures, but that is not evident in the figures above.

6.3.3 Heatwaves

Heatwaves (consecutive days that exceed an extreme threshold) have a greater societal impact than a single daily record temperature. We measure "Heatwave Days" here as the count of all days in May-Sep each year that exceed the 90th percentile for that day and that lie within a period of at least six consecutive days. This is equivalent to the method used in NCA4, except that the reference period here is the entire record 1899-2024 while NCA4 truncated the reference period to 1961-1990, which was a cool interval. That truncation boosts positive results (days exceeding the 90th percentile) in years warmer than the reference period, especially starting in 1960 and moving to the present (see Figure 6.3.6 and discussion below).

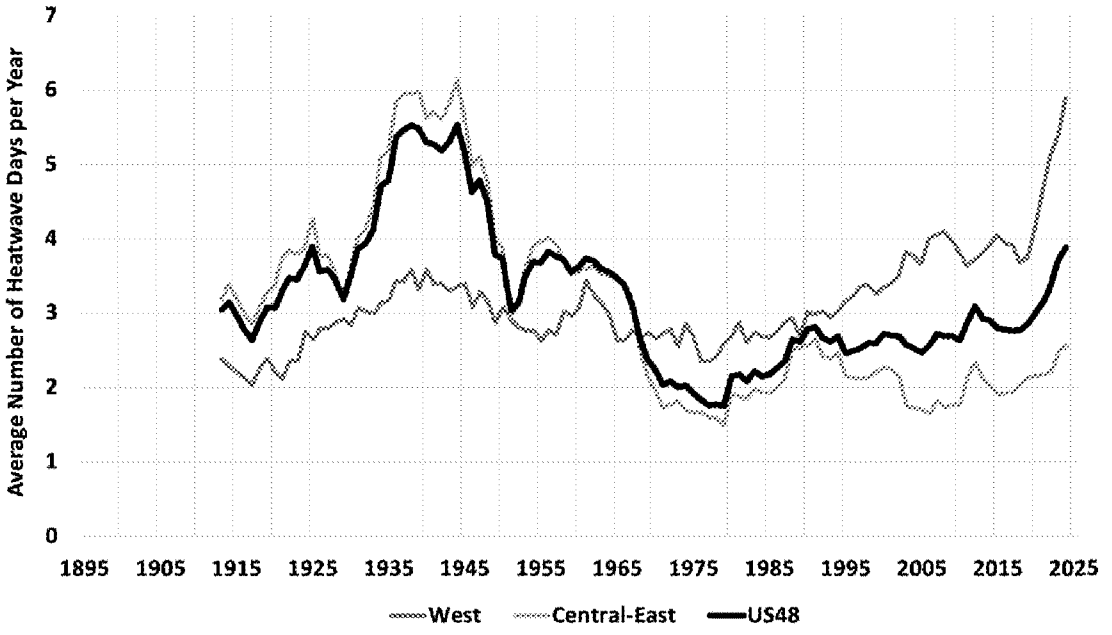

Figure 6.3.6 15-year trailing average of number of heatwave days per year per station in the CONUS (black line) and two regions: West (red), Central-east (green).

Figure 6.3.6 indicates that there are regional variations in heatwave activity. The excessive heat of the first half of the 20th century occurred primarily in the eastern two-thirds of the nation, while the West has seen a recent increase of heatwave days (NCA5). This indicates that the background warm season circulation favored heatwaves in the eastern portions of the country in the first half of the 20th century, but in the 21st century the patterns have favored heatwaves in the West. For CONUS as a whole, heatwaves are no more common today than they were a century ago, consistent with the upper panel of our Figure 6.4.1 taken from NCA4.

This metric varies significantly with region. The four northern regions (Pacific NW, Northern Plains, Upper Midwest, and Northeast) on average experience 15 to 27 heatwave days per 15-year period. In contrast, the five southern regions (Pacific Southwest, 4-Corners, Southern Plains, Ohio Valley and Southeast) see 37 to 54 such days, essentially twice as many. This suggests the summer circulation pattern is more prone to stationary events in the southern regions while transient systems in the northern regions are more common and thus cut short these potentially longer events.

The analysis of heatwaves is an example of why it is important to consider complete datasets and appropriate metrics. The NCA5 directs readers to the website https://www.globalchange.gov/indicators/heat-waves (USGCRP 2023) to view a figure showing the number of urban heatwaves by decade from the 1960s, which we reproduce as Figure 6.3.7.

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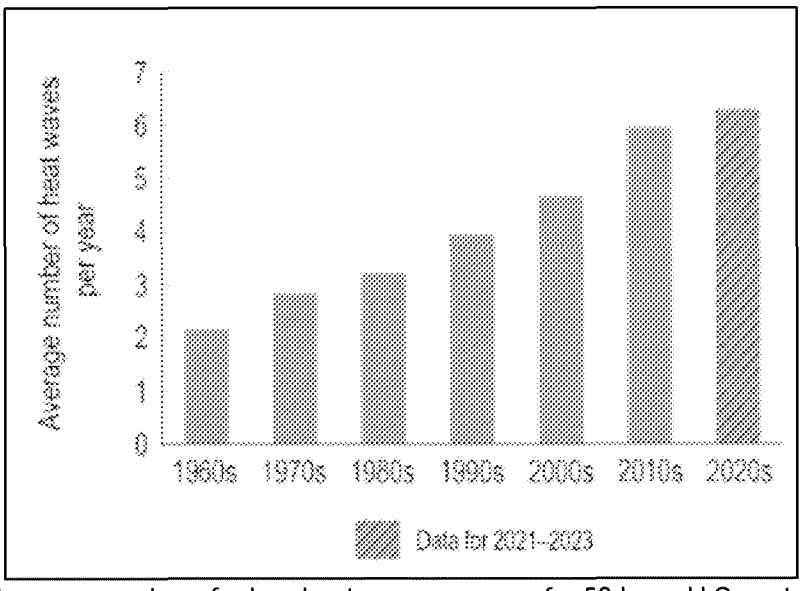

Figure 6.3.7: Average number of urban heatwaves per year for 50 large U.S. metropolitan areas, a misleading metric for reasons explained in the text. From https://www.globalchange.gov/indicators/heat-waves (accessed May 22, 2025).

The figure shows a monotonic increase in each decade from two occurrences per year in the 1960s to six in the 2020s. The definition of a heatwave used is an unusual but practical measure of human discomfort - a period of at least 2 consecutive days when the *minimum* apparent temperature (combination of temperature and humidity) exceeds the 85th percentile. Note too, the dataset is limited to the 50 largest U.S. cities.

Given the unusual heatwave definition and urban focus, these increasing values since 1960 presented in USGCRP (2023) are not informative about long term trends or the influence of GHG emissions for at least two reasons. First, as shown in Figures 6.3.1 and 6.3.6, the 1960s was the coldest decade and 1970s the second coldest decade since the 1910's, so this starting date preconditions the time series to show increases. Second, post-1960 urbanization in these cities is a major factor in the rise of Tmin relative to co-located Tmax and relative to Tmin at nearby rural stations. This does not dismiss the real rise in nighttime temperatures in major U. S. cities and the societal impacts associated with these changes. However, we note for a variety of reasons that summer Tmax (especially in rural areas) is a better metric for detecting changes in heatwaves influenced by changes in the background climate due, for example, to increasing GHGs (Christy *et al.* 2009). For CONUS as a whole, the evidence in this section suggests GHG emissions have had little-to-no effect on heatwaves against the background of urbanization and natural climate variability.

6.4 Extreme precipitation

AR6 assessed that an increase in heavy precipitation has been observed in data starting in the 1950s.

> AR6: The frequency and intensity of **heavy precipitation events have increased** since the 1950s over most land area for which observational data are sufficient for trend analysis (high confidence). (SPM A3.2)

> AR6: In North America, there is robust evidence that the **magnitude and intensity of extreme precipitation has *very likely* increased** since the 1950s. Both [one-day maxima] and [5-day maxima] have significantly increased in North America during 1950-2018. (Chapter 11, p. 1560)

The U.S. National Climate Assessments (NCA4, NCA5) have highlighted an increase in the occurrence of the heaviest precipitation events (defined in different ways) primarily in the eastern half of CONUS, especially the Northeast, when starting the analysis in either 1901 or 1958. Interestingly, the regional variations indicate that the largest increases in extreme precipitation events are in the Northeast and the smallest in the West, a pattern counter to the changes in temperature extremes (Figure 6.3.6).

McKitrick and Christy (2019) examined long-term and consistent station observations of extreme daily precipitation to test some of these NCA claims for the Southeast and West Coast using a trend model with a non-parametric variance estimator robust to the complex autocorrelation properties of precipitation data. When the time series were extended back in time (as far as 1872 in some cases) or started later (1978), there were no significant trends for either region.

These findings have been updated for this report (McKitrick and Christy 2025) with similarly constructed observations from 29 stations on the CONUS Pacific Coast (1893ff from San Diego CA to Blaine WA) and 24 stations in the humid Southeast (1872ff from Austin TX to Washington DC), also adding 27 stations in the Northeast (1888ff from Buffalo NY to Eastport ME). The locations are shown in Figure 6.4.1. The stations were selected based on availability of long-term high-quality records. The regions are each associated with important features of extreme precipitation behavior: the Pacific coast is associated with landfalling atmospheric rivers for which AR6 cites evidence of increasing activity since 1948 with further increases expected as the world warms (AR6 8.3.2.8.2); the NCA report indicates that the Northeast has experienced the greatest increase in extreme events, and the Southeast is also a place noted in the NCAs as having increased extreme events.

The results of applying the analysis of McKitrick and Christy (2019) were as follows for each region, then followed by further explanation.

Pacific Coast heavy rainfall events

- The average precipitation trend is statistically significant (downwards) in Astoria OR; insignificant elsewhere.
- The trend in rainfall variance is positive and significant in Big Sur CA; insignificant elsewhere.
- The trend in daily maximum precipitation is positive and significant in Aberdeen WA and Big Sur CA and negative and significant in Newport OR (insignificant elsewhere).
- Averaged over all stations in the region, none of these three trend parameters is statistically significant.

The Pacific Coast receives considerable precipitation from Atmospheric River (AR) events which often last more than a day or two (e.g., Gershunov *et al.* 2017, Pan *et al.* 2024). The worst series of such events in recent history was the so-called ARkStorm that occurred during December 1861 and January 1862; it dumped nearly 10 feet of rain in parts of California and submerged the entire Central Valley for weeks under as much as 15 feet of water (Brewer 1930, Null and Hulbert 2007). Additionally, Paleoclimate research has found six megastorms more severe than 1861–1862 in California during the last 1800 years, occurring at intervals of 300 years or so (Porter *et al.* 2011).

Figure 6.4.1: Locations of precipitation monitoring stations used in this report. Orange: Pacific coast. Blue: Northeast. Green: Southeast. Data from McKitrick and Christy (2025).

We examine occurrences of 5-day deluges as follows. Taking the Pacific coast as an example, a 130-year span contains 26 5-year intervals. At each location we computed the 5-day precipitation totals throughout the year and selected the 26 highest values across the sample. A single year might have more than one of the 26 heaviest. Each of those can be thought of as 1-in-5yr events. If there are no trends in precipitation, then the total number of these events across all stations should be evenly spread over the years. In Fig. 6.4.2 we show the distribution in time of these events for the Pacific coast. The deluges associated with the massive 1997-98 El Niño event are readily apparent. While erratic, as is typical of such precipitation metrics, there is no indication of a tendency to become more frequent over time.

Southeast heavy rainfall events

- The trend in average precipitation is positive and statistically significant in Mobile AL and Quitman GA but insignificant elsewhere.
- The trend in rainfall variance is positive and significant in Mobile AL but insignificant elsewhere.
- The trend in daily maximum precipitation is positive and significant in Vicksburg MS and Norfolk VA but insignificant elsewhere.
- Averaged over all stations in the region none of these three trend parameters is statistically significant

Figure 6.4.3 is analogous to Figure 6.4.2 for the last 150 years in the Southeast humid zone. The temporal pattern of 5-day totals of the 1-in-5yr heavy events is generally unremarkable, though a cluster of higher values appears in 1995 to 2019. The increase in those years is due largely to the 4 northeastern-most stations of Wilmington NC, Weldon NC, Washington DC, and Norfolk VA. This confirms the pattern indicated in NCA4 and NCA5 -- an increasing frequency of heavy events due to a temporal clustering of tropical storms from eastern NC to Maine discussed below. Otherwise, the remaining 20 stations show an unremarkable temporal distribution of heavy events.

BOX: Perils of short data records

San Francisco provides a good case study of the limitation of using short historical samples to characterize natural variability of extreme events. Suppose we use a 130-year sample of daily San Francisco precipitation from 1895 to 2024 and we look for 3-day, 5-day, 14-day and 30-day rainfall records. The results are as shown in Table 7.2.

Event	Record (inches)	Year
3-day	6.94	2023
5-day	8.55	2023
14-day	12.62	2023
30-day	18.93	1998

Table 6.2: Extreme rainfall records, San Francisco, 1895-2024.

The records all cluster in the more recent years. 2023 appears to be an exceptional year and since it is near the end of the sample, it might suggest that the climate has shifted into a more hazardous state, perhaps because of human influences. [Note "2023" indicates the event occurred in the water-year of Aug 2022 to Jul 2023.]

But the picture is very different if we use a sample that begins 45 years earlier, in 1850. Table 6.3 shows that the record-setting events all happened in the 1860s. Furthermore 2023 is now not even in 2nd place but falls to 3rd or 4th place. And comparing the records of the two charts shows the extreme precipitation events in 1862 and 1867 involved considerably more rainfall than the 1998 and 2023 events, with 14- and 30-day totals about 50 percent higher.

Event	Record (inches)	Year	Rank of 130-yr extreme listed in Table 6.2
3-day	8.85	1867	3
5-day	9.80	1867	3
14-day	19.05	1862	4
30-day	28.25	1862	2

Table 6.3: Extreme rainfall records, San Francisco, 1850-2024.

The range of natural variability is made even more remarkable when paleoclimate evidence is examined. Porter *et al.* (2011) discovered that in the past 1,800 years at least six megastorms were more intense than the devastating 1861-62 ARkStorm that struck the region. Evidently such extreme events, "unprecedented" in our 1895-2024 sample, have impacted the region about every 300 years, though not since 1895.

This example illustrates the limitations of using relatively short climate periods (~130 years) to assess the character and range of natural variability in general and of extreme events in particular. Accurate representation of the full range of natural variability is necessary for any attribution analyses (Section 8.6). Infrastructure planners, emergency management institutions and attribution scientists would understand the significant mischaracterization of the magnitude of a future extreme if based only on the last 130 years. In this case, a single time-sample of 130 years provides an underestimation of the extreme value by up to 50 percent determined when adding only 45 more years of observations. Compared to millennial-scale paleoclimate evidence, an even greater underestimation would occur. An important lesson is that the climate can deliver great surprises on its own, even without human influences.

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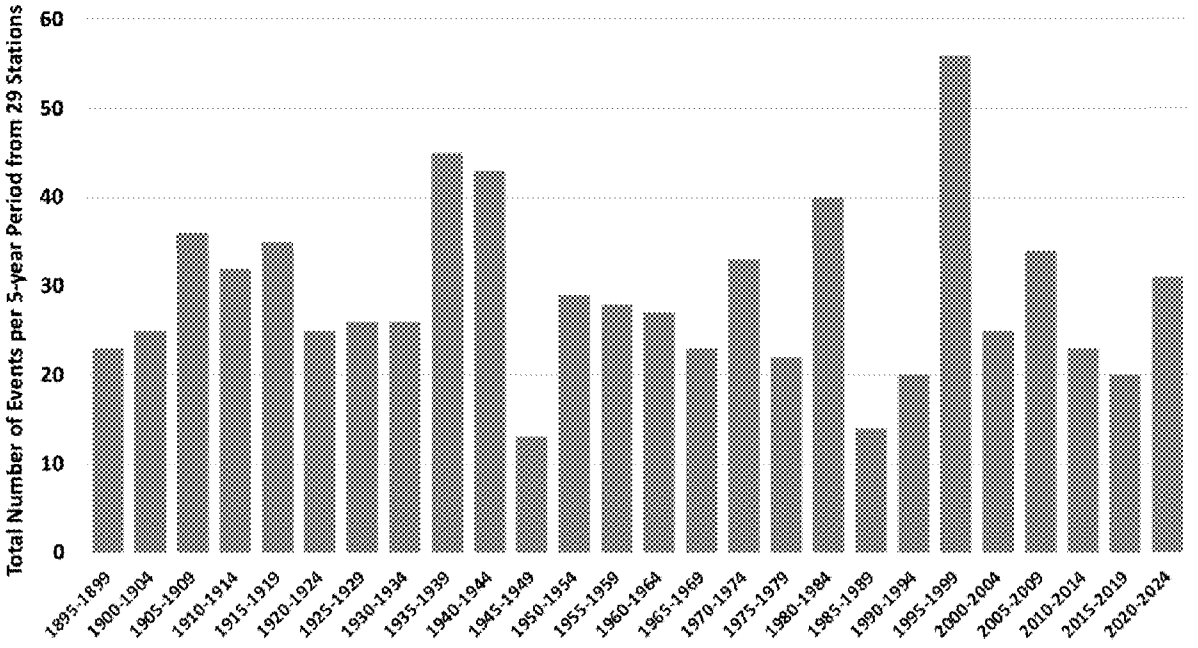

Figure 6.4.2. The time distribution by 5-year periods of the 26 heaviest (1-in-5 yr) occurrences for 29 stations on the Pacific coast.

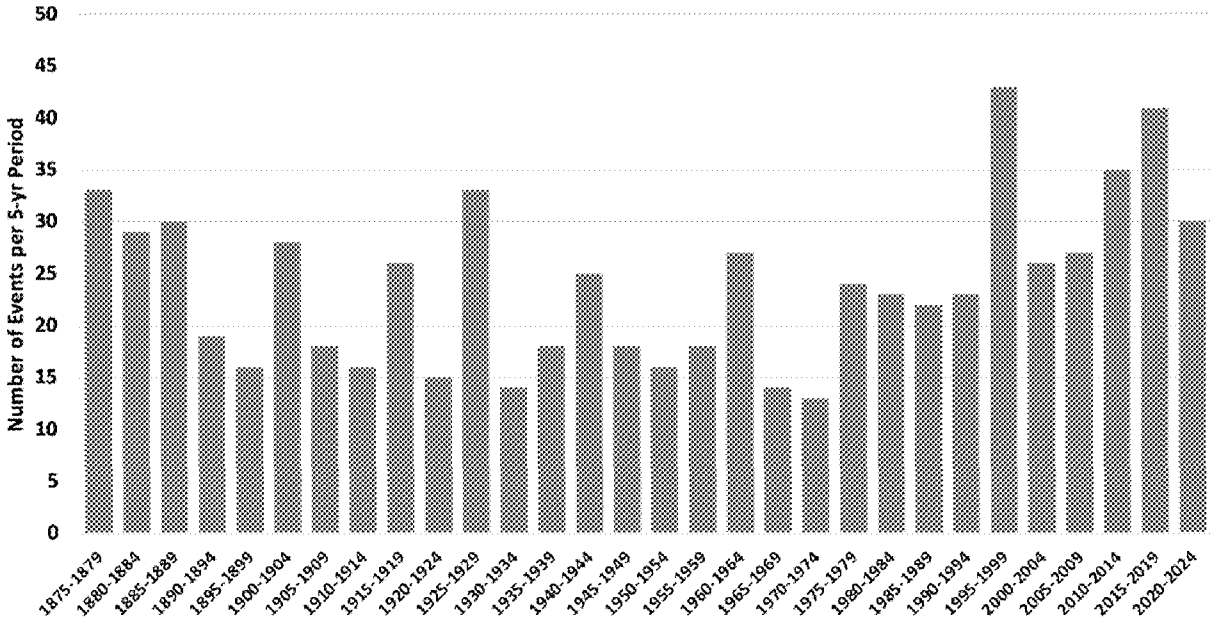

Figure 6.4.3. As in Fig. 6.4.2 but for the heaviest 30 (1-in-5yr) events for 24 stations in the humid Southeast from Austin TX to Washington DC in 5-year bins for 1875-2024.

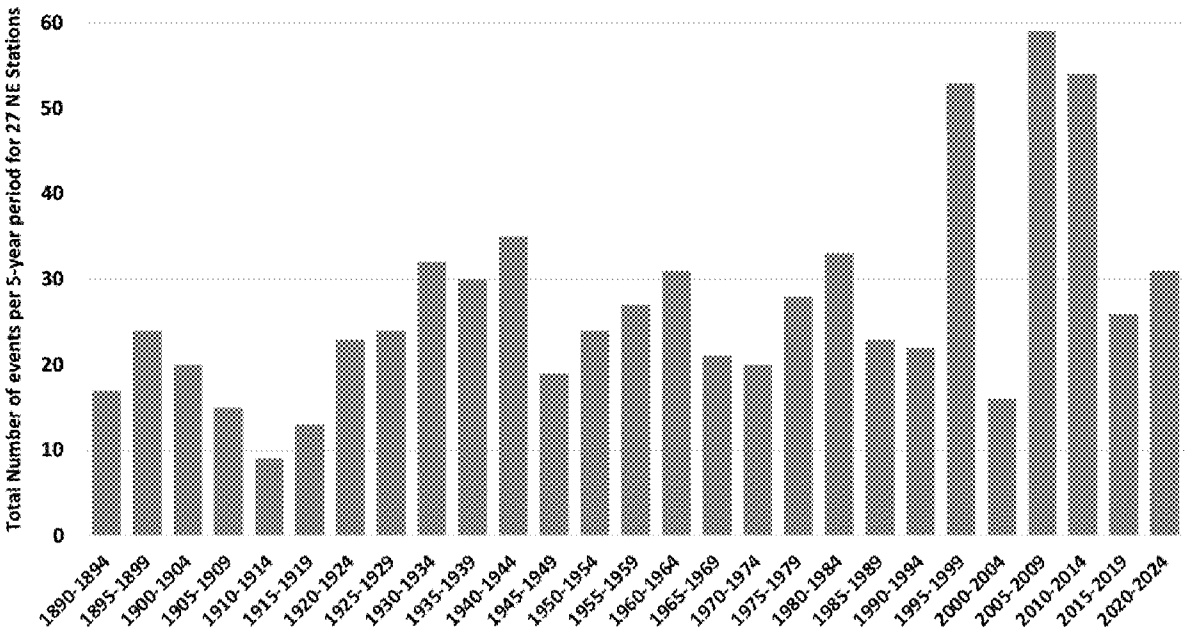

Figure 6.4.4. As in Fig. 6.4.2 but for the heaviest 27 (1-in-5yr) 3-day precipitation events for 27 Northeast stations from NY to ME, including Montreal.

Northeast heavy rainfall events

- The trend in average precipitation is positive and statistically significant in 12 of 27 locations and also in the regional average.
- The trend in rainfall variance is positive and significant in Portland ME, Albany NY, Buffalo NY and Eastport ME but insignificant elsewhere.
- The trend in daily maximum precipitation is positive and significant in Portland ME, Gardiner ME and Eastport ME but insignificant elsewhere.
- When averaged over all stations in the region, there is no statistically significant trend in either the precipitation variance or maximum

Fig. 6.4.4 is analogous to Figure 6.4.2 for the last 135 years in 27 stations in the Northeast (including Montreal Canada). We use 3-day totals here as this produced the largest temporal variations in time. In this region, 77 percent of events occur during June to October and are dominated by incursions of hurricanes, tropical storms, or tropical storms that transition to extratropical systems. According to NCA4 and NCA5 this region experienced the largest increases in extreme events, so it merits a closer examination.

There is a noticeable clustering of extreme events from 1995 to 2014. Howarth *et al.* (2019) examined a similar region as in Fig. 6.4.4 that includes PA and NJ and reported significant differences in various precipitation extremes between two 18-year periods, 1979-96 and 1997-2014. That included a 317 percent increase in 24-hr events exceeding 6 inches, while we find a 58 percent increase over the same years. However, Figure 6.4.4 shows that frequency drops sharply after 2014, returning to the long-term average in the subsequent 5-year intervals, again illustrating the perils of drawing conclusions from short-term trends in highly variable metrics.

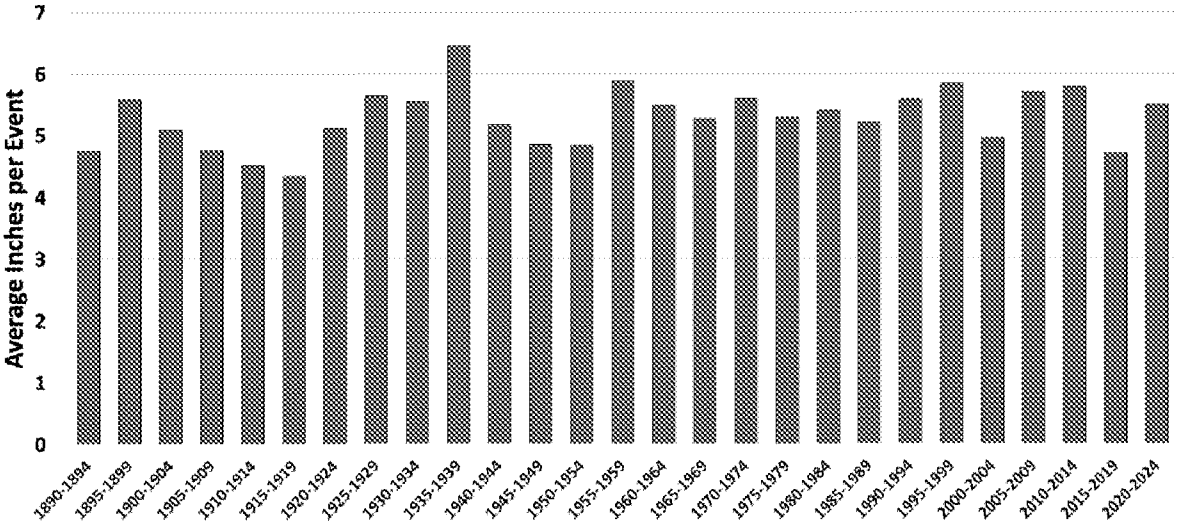

Figure 6.4.5. Average amount of precipitation falling in the 1-in-5yr events for the NE stations.

The high percentage increase in the Howarth *et al.* sample is associated with small numbers at relatively few locations: there were only 6 in the first period and 25 in the second across 58 stations. Most of the stations did not record such an event. If there is a region-wide increase in heavy events, it should be seen in the average across all stations. Figure 6.4.5 shows the average precipitation in the 1-in-5 yr events across the NE. The trend is only +0.04 inches/decade. The highest amount, 1935-39, includes the Great New England Hurricane of 1938, one of the rare major (Category 3 or higher) hurricanes to strike the region. The results in Figs. 6.4.4 and 6.4.5 thus suggest that though there was a surge in the number of events at a few locations during the 1995 to 2014 interval, there was no regional pattern and the change did not persist beyond 2014.

Jong *et al.* (2024) document the increase of tropical influences on precipitation events in the Northeast since 1959 and concluded "The autumn extreme precipitation trend over the Northeast U.S. is primarily attributed to tropical cyclone-related events since the 1990s." The question then becomes: "Was the temporal clustering of tropical systems in 1997-2014 which affected the Northeast a response to increasing GHGs?" Jong *et al.* examined CMIP-6 model output which suggests that there will be fewer such systems in the 21st century but that the intensity of the rainfall events might increase. This conjecture is not seen in Fig. 6.4.5 where the amount-per-event has remained steady over the 135-year period.

There is some evidence to indicate the heaviest rainfall events might be redistributed due to the impact of urban infrastructure on the local weather (e.g., Pielke Sr. *et al.* 2011, Zhang *et al.* 2018, Yang et al. 2024). Yang *et al.* state "Cities that experience compact development tend to witness larger increases in extreme rainfall frequency over downtown than their rural surroundings, while the anomalies in extreme rainfall frequency diminish for cities with dispersed development." While this is an important insight to consider, the effect on the specific stations used in this analysis is unknown, or at least not detectable in Fig. 6.4.5.

In summary, some U.S. regions show short-duration increases in extreme precipitation events, consistent with natural variability. But analysis of long term, nationwide historical records that considers the autocorrelation properties of precipitation data does not support the claim that extreme short-duration rainfall events are becoming more frequent or intense.

6.5 Tornadoes

AR6 assesses tornado trends in the U.S. as follows:

> [O]bservational trends in tornadoes, hail, and lightning associated with severe convective storms are not robustly detected due to insufficient coverage of the long-term observations. There is *medium confidence* that the mean annual number of tornadoes in the USA has remained relatively constant. (Chapter 11, section 11.7.3, p. 1594)

The monitoring of weak tornadoes has changed over time. The growth of rural populations and the increasing ability to take video with hand-held devices has led to more frequent reports of weak tornadoes that produce minimal damage. In contrast, strong to violent tornadoes have been observed more consistently over time. Note that tornado strength is measured by the damage it produces, not by the visual appearance of the funnel. Limited real-time observational capabilities in earlier decades did not prevent identification because strong to violent tornadoes leave much more damage which will be assessed later even if the tornado itself was not observed. Since statistics began in 1950, there has been a substantial decrease (by about 50%) in the number of strong to violent tornadoes as shown in Fig. 6.5.1a.

To summarize, there is a noticeable downward trend in the number of severe tornadoes in the U.S. since 1950. After 1990 the number of weak tornadoes in the U.S. has remained roughly constant; data before that are incomplete due to limited monitoring.

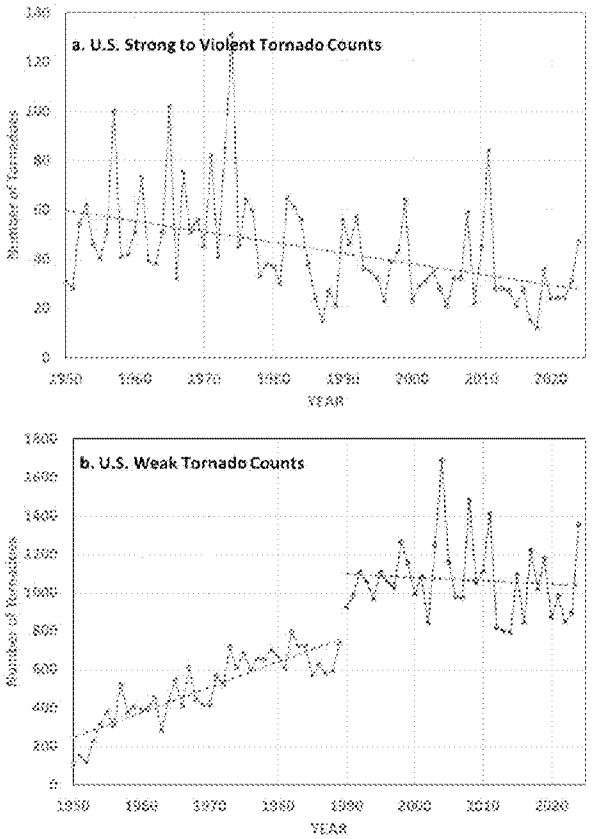

Figure 6.5.1. Annual U.S. tornado counts for (a) strong to violent tornadoes (EF3 to EF5), and (b) weak tornadoes (EF0 to EF2). Based upon NOAA Storms

Prediction Center data, available at https://www.spc.noaa.gov/wcm/data/1950-2024_actual_tornadoes.csv

6.6 Flooding

Changes in floods were assessed as follows:

> AR6: The SREX **assessed *low confidence* for observed changes in the magnitude or frequency of floods** at the global scale. This assessment was confirmed by the AR5 report. The SR15 found increases in flood frequency and extreme streamflow in some regions, but decreases in other regions. . . [H]ydrological literature on observed flood changes is heterogeneous, focusing at regional and sub-regional basin scales, making it difficult to synthesise at the global and sometimes regional scales. (Chapter 11.5)
>
> AR6: [T]he seasonality of floods has changed in cold regions where snowmelt dominates the flow regime in response to warming (*high confidence*). Confidence about peak flow trends over past decades on the global scale is ***low***. (Chapter 11.5)
>
> NCA4: Trends in extreme high values of streamflow are **mixed** across the United States. Analysis of 200 U.S. stream gauges indicates areas of both increasing and decreasing flooding magnitude **but does not provide robust evidence** that these trends are attributable to human influences (pp. 240-241)

The absence of detectable US-wide trends in flooding is consistent with the findings in Section 6.4 of absence of coherent changes in extreme precipitation.

6.7 Droughts

Assessments of drought trends were as follows.

> AR6: Few AR6 regions show observed increases in meteorological drought (Section 11.9, p. 1575),
>
> AR6: Increasing trends in agricultural and ecological droughts have been observed on all continents (*medium confidence*), but decreases only in one AR6 region (*medium confidence*). Increasing trends in hydrological droughts have been observed in a few AR6 regions. (Chapter 11 Summary)
>
> NCA4: As a consequence of this increased precipitation, **drought statistics over the entire CONUS have declined**. (p. 233)
>
> NCA4: Recent droughts and associated heat waves have reached record intensity in some regions of the United States; however, by geographical scale and duration, the Dust Bowl era of the **1930s remains the benchmark** drought and extreme heat event in the historical record (very high confidence). (p.231)
>
> SREX: From a paleoclimate perspective, **recent droughts are not unprecedented**, with severe 'megadroughts' reported in the paleoclimatic record for Europe, North America, and Australia. (p. 170)

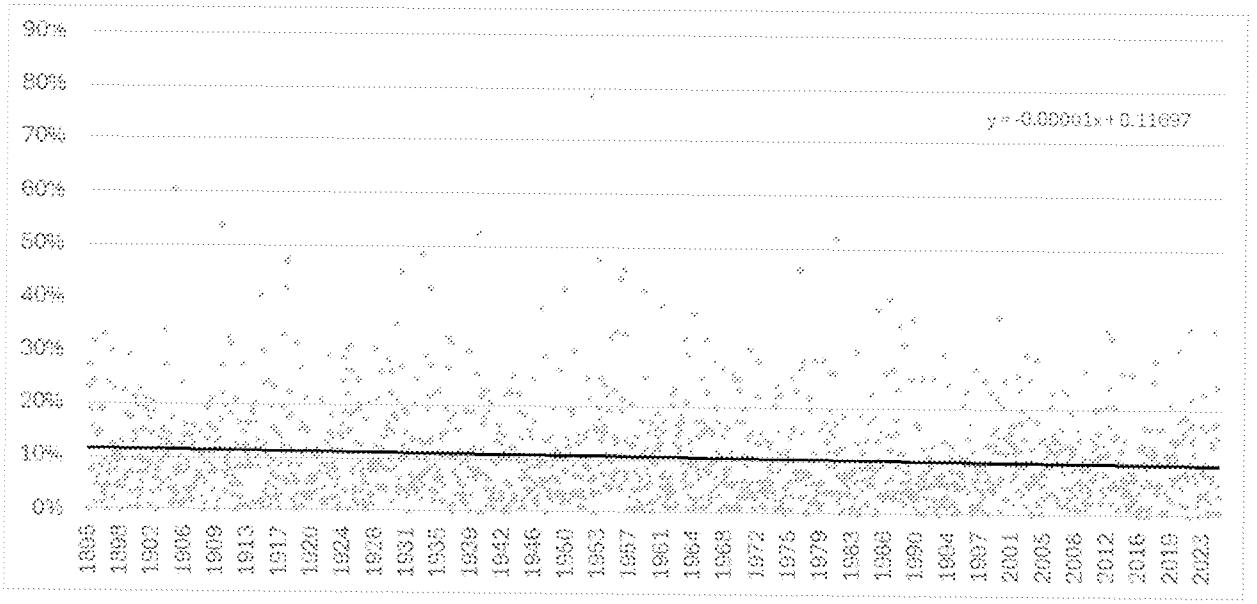

Figure 6.7.1: Monthly percent of US classified as "Very Dry" 1895—2025. Data source: NOAA https://www.ncei.noaa.gov/access/monitoring/uspa/wet-dry/0 least squares trendline added.

As shown in Figure 6.7.1, U.S. long-term data shows an insignificantly declining trend in extreme dryness (-0.001 percent per year)

Kogan *et al.* (2020) examines a 38-year high-resolution satellite-based drought measure and concludes that global drought has not intensified and is not connected to climate change: "it is possible to state firmly that global and main grain countries' drought area and intensity trends have not been following global climate warming since 1980's."

In summary there is no evidence of increasing drought frequency or intensity in the U.S. or globally over recent decades.

6.8 Wildfires

The IPCC has not provided an assessment of wildfires. As shown in Figure 6.8.1, global wildfire activity as measured by European Space Agency shows a downward trend in the 21st century.

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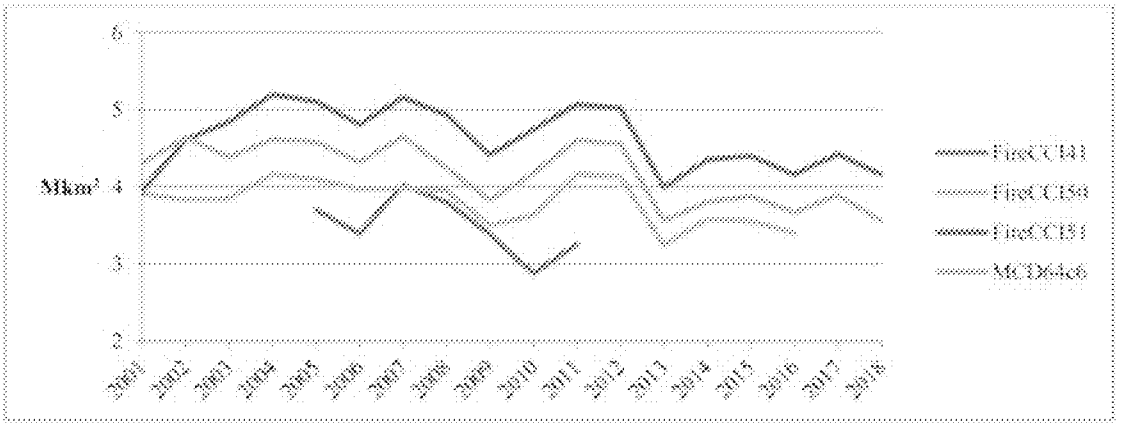

Figure 6.8.1: Global wildfire area 2001-2018. Source: From Lizundia-Loiola *et al.* (2021) Figure 12. The different coloured lines represent data products derived from different satellites and algorithms

Global data show that wildfire coverage is constant or declining on every continent (Samborska and Ritchie, 2024).

Active fire suppression since 1900 makes it difficult to establish a natural baseline for wildfire activity in the U.S. Paleoclimatic evidence indicates that past activity was much higher than today. Marlon *et al.* (2012) used sedimentary charcoal layers to reconstruct fire history of western U.S. for the past 1400 years and also fit a model to predict fire activity as a function of climatic conditions. Their results are summarized in Figure 6.8.2 below (from Figure 2 in their paper). There has been a growing wildfire deficit over the 20th century. In other words, however much fire was observed in the 20th century, it was less than what would have been observed in previous centuries based on the climatic conditions. Parks *et al.* (2025) likewise find that despite the recent increase in wildfire burn area in North America, a significant wildfire deficit remains relative to historical wildfire regimes.

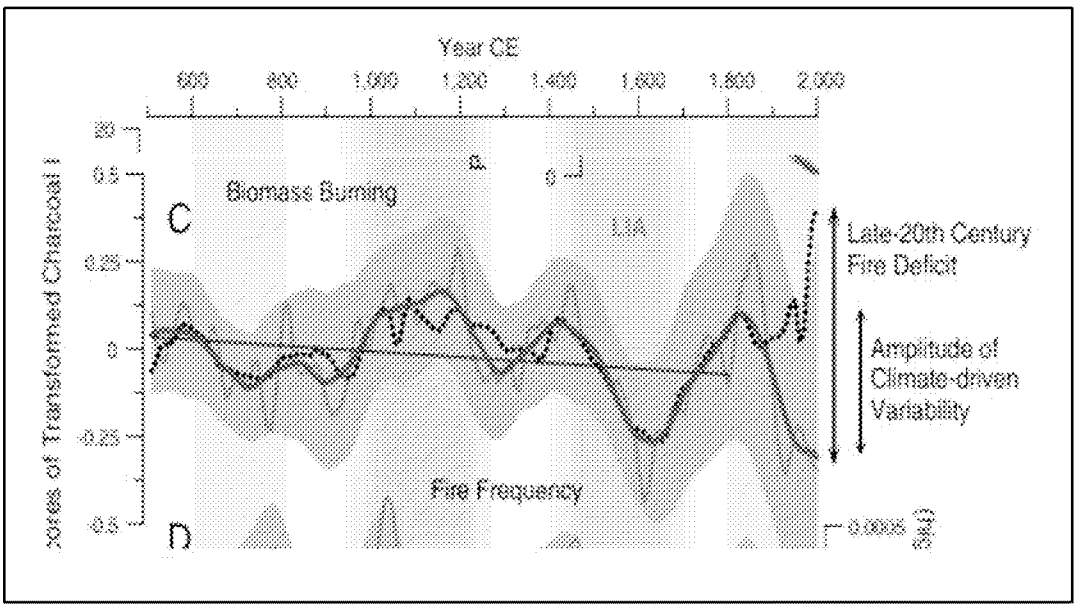

Figure 6.8.2 Fire frequency and fire deficit in the US. The red line shows the smoothed charcoal record and the black dotted line shows the predicted charcoal record based climatic conditions. model. Source: Marlon *et al.* (2012) Figure 2.

U.S. data from the National Interagency Fire Centre (NIFC) from 1926 to 2023 are shown in Figure 6.8.3. The NIFC has removed the pre-1960 data from its current website on the grounds that measurement methods changed after 1960 making the comparison unreliable. Nonetheless just focusing on the post-1985 interval the number of fires is not increasing. The area burned did increase but only until about 2007.

Forest fires have always been a part of nature, and they can certainly create conditions that are inhospitable in the short term for all life, including humans. Science has confirmed the overall benefit and necessity of forest fires. While recent high-profile fires and seasons serve as a reminder of the potential destructive impact, the highest profile U.S. forest fire remains the 1910 Big Blowup fire in the U.S. west, which destroyed over three million acres and eliminated entire towns like Taft, MT (Apple, 2020). The 1910 fire reshaped the U.S. Forest Service (National Forest Foundation 2022) leading to a focus on fire suppression with a primary goal of defeating all forest fires (Forest History Society, 2022). This led to the "10 am rule" in 1935 requiring that all fires spotted on any day had to be controlled by 10 am the following day (National Forest Foundation, 2022).

While defeating all fires seemed a noble goal, questions began to arise as to whether this behavior "followed the science" (U.S. Forest Service, 2022). Over time the U.S. Forest Service has begun to rethink its goals, recognizing that new approaches such as prescribed burns, fuel elimination, and controlled wildfires are more appropriate (Sommer, 2016). Recent research is validating this approach and recognizing that more frequent smaller fires likely result in healthier forests, water ecosystems and biodiversity (Stephens *et al.*, 2021).

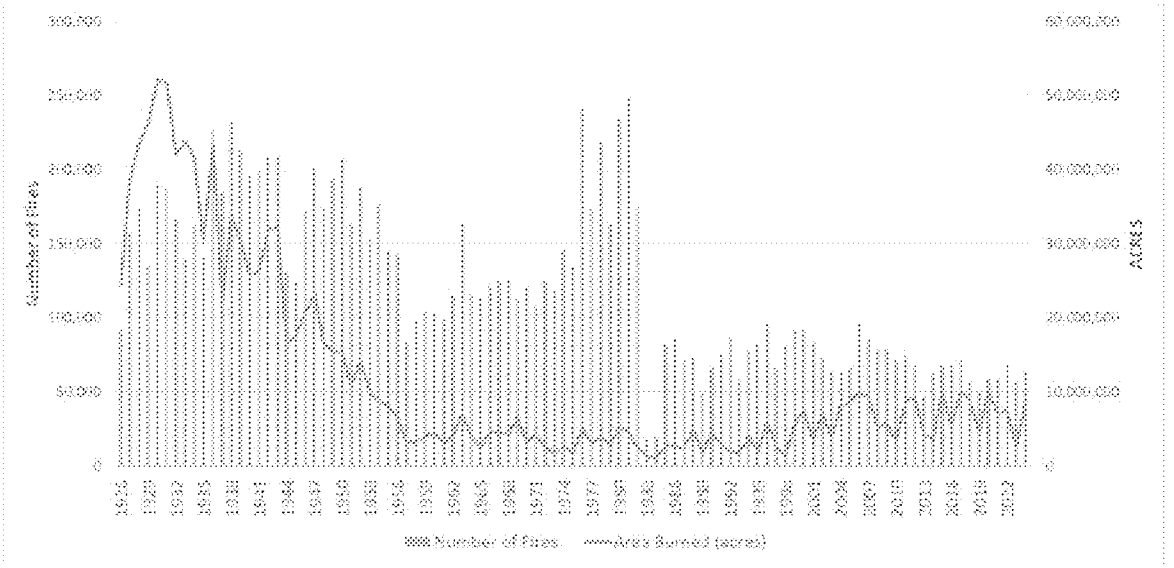

Figure 6.8.3: U.S. wildfires 1926 to 2023. Source: Post-2018: National InterAgency Fire Center data https://www.nifc.gov/fire-information/statistics/wildfires. Pre-2017 webarchive.org (n.d.).

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7 CHANGES IN SEA LEVEL

Chapter Summary

Since 1900, global average sea level has risen by about 8 inches. Sea level change along U.S. coasts is highly variable, associated with local variations in processes that contribute to sinking and also with ocean circulation patterns. The largest sea level increases along U.S. coasts are Galveston, New Orleans, and the Chesapeake Bay regions - each of these locations is associated with substantial local land sinking (subsidence) unrelated to climate change.

Extreme projections of global sea level rise are associated with an implausible extreme emissions scenario and inclusion of poorly understood processes associated with hypothetical ice sheet instabilities. In evaluating the IPCC AR6 projections to 2050 (with reference to the baseline period 1995-2014), almost half of the interval has elapsed by 2025, with sea level rising at a lower rate than predicted. U.S. tide gauge measurements reveal no obvious acceleration beyond the historical average rate of sea level rise.

7.1 Global sea level rise

Global sea level rise is arguably the most important climate impact driver that is unambiguously associated with increasing temperatures. At the global level, warming raises sea level through thermal expansion of sea water and through melting of glaciers and ice sheets. Variations in land water storage are another important factor. At the regional scale, sea level change is influenced by large-scale ocean circulation patterns, and geologic processes and deformation from the redistribution of ice and water. Locally, vertical land motion from geologic processes, ground water withdrawal, and fossil fuel extraction are also important.

The IPCC AR6 estimates that global mean sea level increased by 7.9 (5.9–9.8) inches between 1901 and 2018, with the rate of sea level rise accelerating in recent decades. At the ocean basin scale, sea levels have risen fastest in the Western Pacific and slowest in the Eastern Pacific over the period 1993–2018 (Fox-Kemper *et al.*, 2021). The rate of global sea level rise is estimated to be 0.12 inches/year, about the height of two stacked pennies (NASA, 2020).

The observing systems for global sea level rise have advanced significantly in the satellite era, particularly with the advent of satellite altimeters in 1993. Local tide gauges have provided useful data for the past century, and even longer for a few locations. Following the end of the Little Ice Age in the mid-nineteenth century, tide gauges show that the global mean sea level began rising during the period 1820–1860, well before most anthropogenic greenhouse gas emissions.

7.2 U.S. sea level rise

Observed and predicted rates of mean global sea level rise might have little scientific relevance for specific locations, owing to local processes (NOAA, 2025). Figure 7.1 shows that in Canada and Alaska (and also northern Washington), sea level is decreasing, owing to uplift from glacial rebound. Most of the Pacific coast tide gauges show low rates of sea level rise, while largest U.S. rates are on the Gulf coast (Louisiana and Texas) and in the mid-Atlantic states (Chesapeake Bay region).

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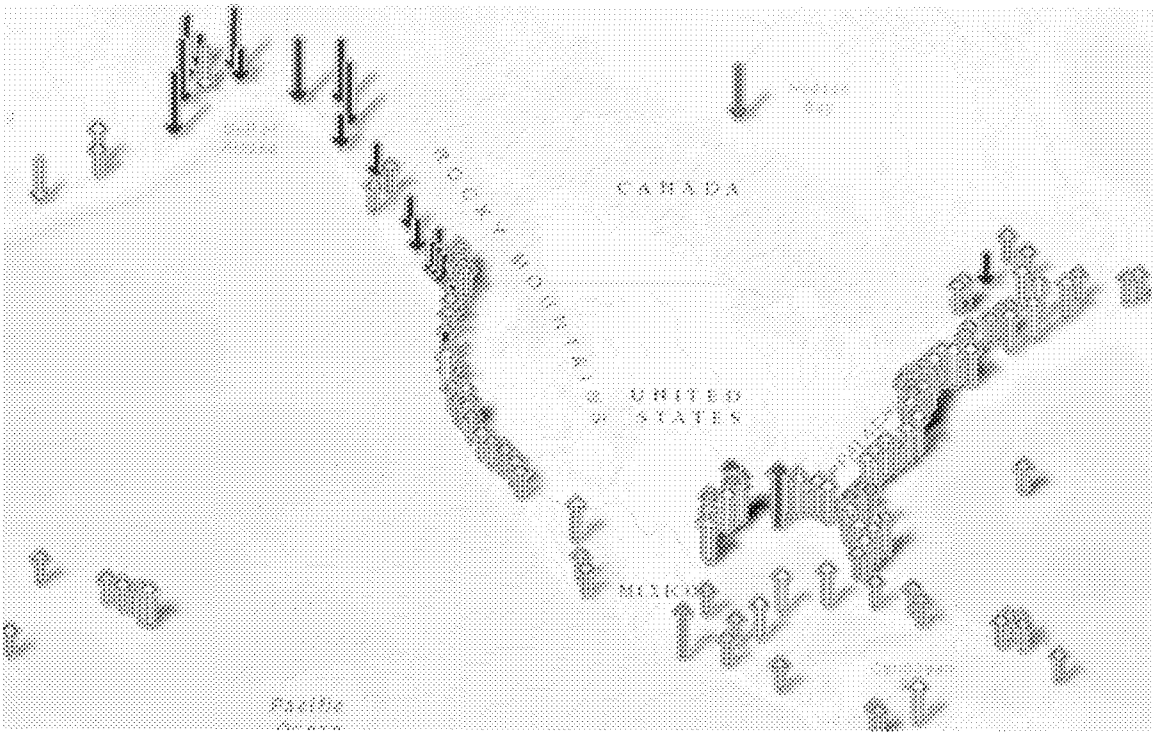

Figure 7.1. Map of rates of relative sea level rise along the U.S. coast (NOAA, https://tidesandcurrents.noaa.gov/sltrends/). For reference, 3 mm = 0.12 in.

Measurements of relative sea level rise from tide gauges conflate the climatologically relevant increase in the volume of seawater with local vertical land motion. The latter, which varies from place to place, is best measured using a Global Positioning System (GPS) station located near the tide gauge. It is driven by a range of processes that can be comparable to the climate signal and can locally exacerbate (subsidence/sinking) or mitigate (uplift) the risk of sea level rise (Wöppelmann and Marcos, 2016). Human activities triggering subsidence are often significant. They include soil drainage (*e.g.* for urban development) and subsurface extraction of groundwater or hydrocarbons.

Table 7.1 shows absolute sea-level rise (ASLR) for selected locations, determined from the sum of uncorrected sea-level rise as estimated from tide gauge time series (RSLR) (NOAA, 2025) and the vertical land motion (VLM) measurements (NAS, 2012; Letetrel *et al.*, 2015; Karegar *et al.*, 2016). The absolute sea level rise for each of these locations is significantly smaller than the measured relative sea level rise owing to local subsidence. More than half of the measured relative sea level rise is attributed to land sinking for these locations: San Francisco, Galveston, Grand Isle. For reference, the global average rate of absolute sea level rise is estimated to be 0.12 inches/year.

Location	RSLR	VLM	ASLR
San Francisco, CA	+0.08	-0.06	+0.02
Galveston, TX	+0.26	-0.19	+0.07
Grand Isle, LA	+0.36	-0.28	+0.08
St Petersburg, FL	+0.12	-0.02	+0.10
New York City, NY	+0.11	-0.05	+0.06

Table 7.1 Absolute sea level rise (inches/year) consisting of Relative Sea Level Rise (RSLR) plus Vertical Land Motion (VLM)

San Francisco Bay

Over the past 100 years, relative sea level in the San Francisco Bay area has risen by 7.8 inches, at an average rate of 0.08 inches/year (Figure 7.2). As shown in Table 7.1, San Francisco's vertical land motion is -0.06 inches/year (sinking), producing a recent absolute rate of +0.02 inches/year. Portions of Treasure Island, San Francisco International Airport, and Foster City are sinking as fast as 0.4 inches/year (Shirzaei and Bürgmann, 2018). Problems in the San Francisco Bay area, including threats to the airport, are caused primarily by soil compaction in landfill zones that were formerly wetlands, not by the slow creep of global sea level rise.

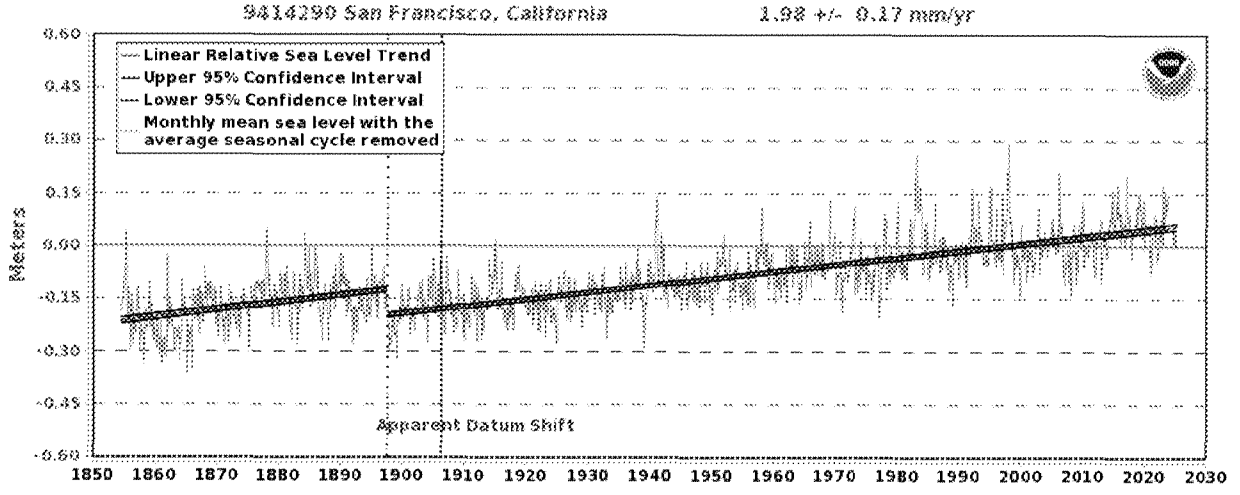

Figure 7.2. Tide gauge measurements at San Francisco, California, obtained from NOAA - https://tidesandcurrents.noaa.gov/sltrends/sltrends_station.shtml?id=9414290 (downloaded 4/22/25).

Galveston - Houston

Long-term tide measurements at Galveston Pier 21 show sea level rise of 2.18 feet in the past century, or a rate of 0.26 inches/year (Figure 7.3). Vertical land motion (subsidence) at Galveston is estimated at -0.19 inches/year, yielding an absolute rate of rise of +0.07 inches/year (Table 7.1). The U.S. Geologic Survey found that most of the land-surface subsidence in the Houston-Galveston region is a direct result of groundwater withdrawals (Kasmarek and Ramage 2017), which caused compaction of the aquifer sediments, mostly in the fine-grained silt and clay layers. By 1979, as much as 10 feet of subsidence had occurred in Houston.

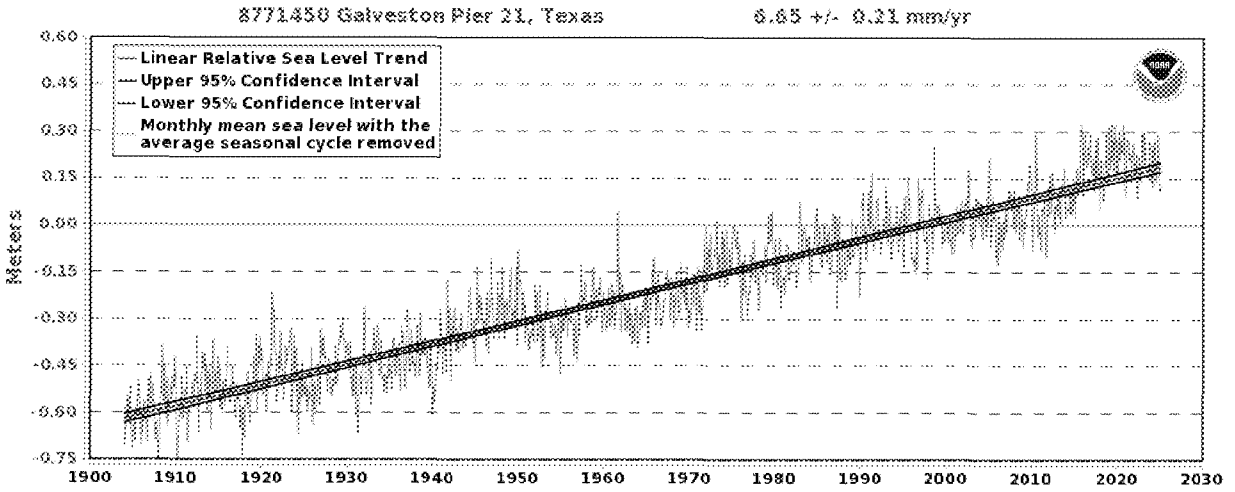

Figure 7.3. Tide gauge measurements Galveston Pier, TX, obtained from NOAA - https://tidesandcurrents.noaa.gov/sltrends/sltrends_station.shtml?id=8771450 (downloaded 4/22/2025).

New Orleans and the Mississippi delta

Long-term tide gauge measurements at Grand Isle, Louisiana, show that sea level has risen by slightly more than 3 feet over the last 100 years at an average rate of 0.36 inches/year (Figure 7.4). Vertical land motion (subsidence) is estimated -0.28 inches/year. Table 7.1 gives the absolute sea level rise as +0.08 inches/year.

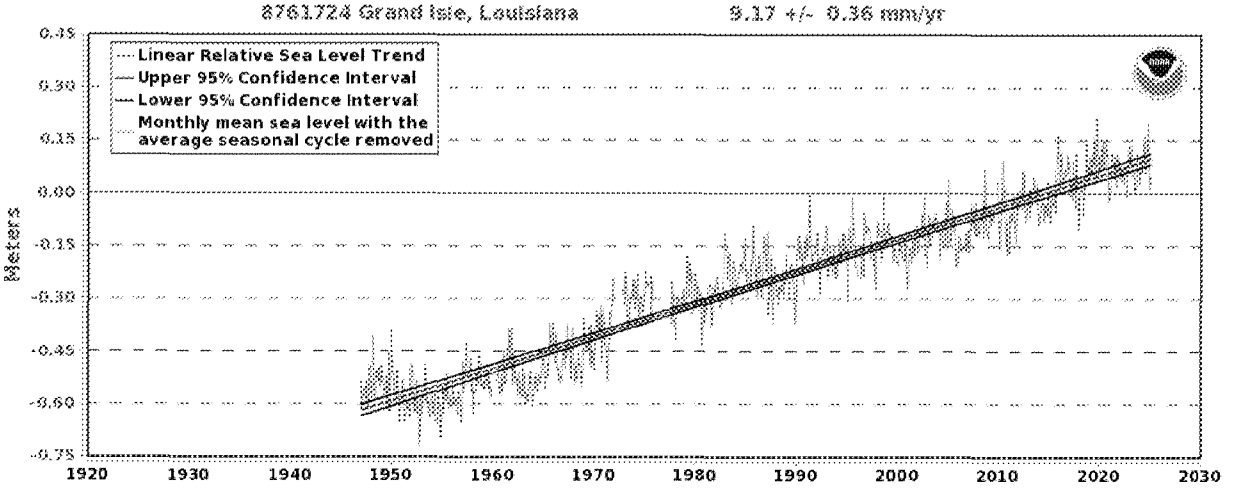

Figure 7.4. Tide gauge measurements at Grand Isle, LA, obtained from NOAA - https://tidesandcurrents.noaa.gov/sltrends/sltrends_station.shtml?id=8761724 (downloaded 4/22/25).

The issues of sea level rise and land loss in the Mississippi Delta region are complex, with geological subsidence and the decline in sediment transported by the Mississippi River being the dominant drivers. The construction of dams in the basin since the 1950s has decreased the Mississippi's suspended sediment load by ~50 percent (Maloney 2018). A new subsidence map of coastal Louisiana finds the coastal region to be sinking at about one third of an inch per year (Neinhuis *et al.* 2017), associated with groundwater and resource withdrawal. As the city's elevation averages one to two feet *below* sea level, sea level rise from anthropogenic warming is hardly the dominant driver of New Orleans' problems.

New York City

New York City is particularly vulnerable to the effects of sea level rise because it is built primarily on islands and has 520 miles of coastline. Measurements by a tide gauge at the southern tip of Manhattan (The Battery) show that relative sea level has risen over 11 inches over the past century, at an average rate of 0.11 inches/year (Figure 7.5). But vertical land motion in the New York City area is -0.05 inches/year (roughly 5 inches per century), so that the absolute rate of sea level rise at The Battery is 0.06 inches/year, or about 55 percent of the measured relative sea level rise.

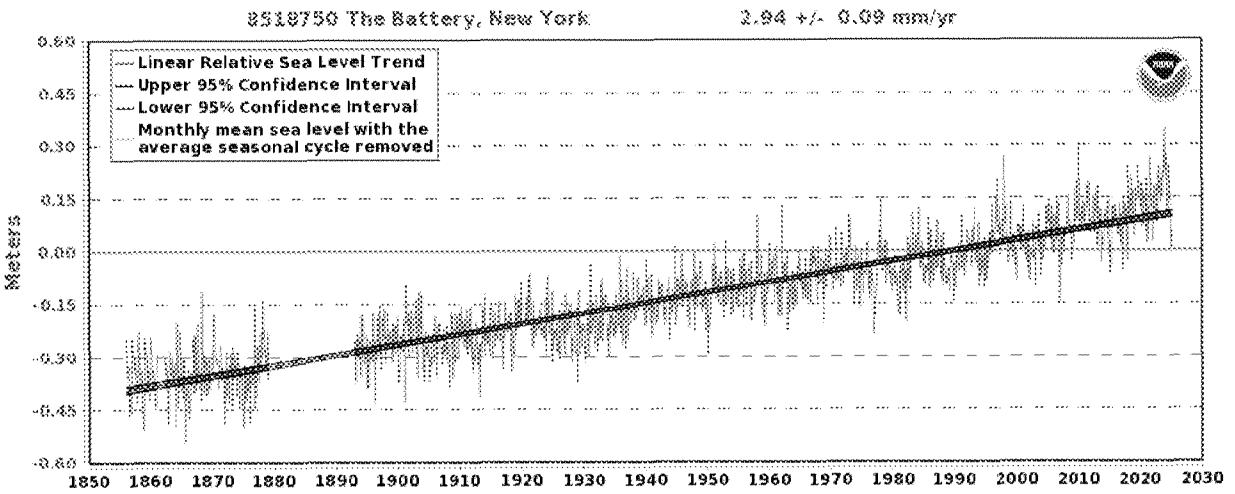

Figure 7.5. Tide gauge measurements at The Battery, New York, obtained from NOAA - https://tidesandcurrents.noaa.gov/sltrends/sltrends_station.shtml?id=8518750 (downloaded 4/22/25).

7.3 Projected sea level rise

The concern over sea level rise is not about the roughly eight inches of global rise since 1900. Rather, it is about projections of *accelerated* rise based upon simulations of a warming climate through the 21st century.

AR6 finds *high agreement* across published global mean sea level projections for 2050 with little sensitivity to emissions scenarios. Considering only projections incorporating ice-sheet processes in whose quantification there is at least *medium confidence*, the global sea level projections for 2050, across all emissions scenarios, fall between 3.94 and 15.75 inches (5th–95th percentile *very likely* range) relative to the 1995–2014 baseline period (Fox-Kemper *et al.*, 2021).

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Conversely, AR6 states there is *low agreement* across published global mean sea level projections for 2100, particularly for higher emissions scenarios. Considering only projections representing ice sheet processes in whose quantification there is at least *medium confidence*, the AR6 global mean sea level projections for 2100 lie between 7.87 and 39.37 inches (5th–95th percentile *very likely* range) under the medium emissions scenario SSP2–4.5 (Fox-Kemper *et al.*, 2021). There is deep uncertainty surrounding projections of sea level rise to 2100 owing to uncertainties in ice sheet instabilities, particularly for the higher emissions scenarios.

In February 2022, NOAA issued its projections of sea level rise for various sites along the U.S. coast (Sweet *et al.*, 2022). They claim that by 2050, the sea will have risen one foot at The Battery in Manhattan (relative to 2020). A one-foot rise in thirty years would be more than twice the current rate and about three times the average rate over the past century. In that historical context, NOAA's projection is remarkable—as shown in Figure 7.6, it would require a dramatic acceleration beyond anything observed since the early 20th century. But even more noteworthy is that Sweet *et al.* (2022) say this rise is "locked in"—it will happen no matter what future emissions are. We should know in a decade or so whether that prediction has legs.

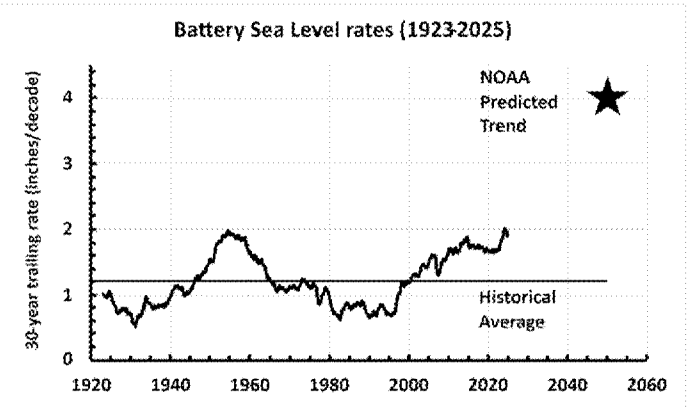

Figure 7.6 Rate of sea level rise at the Battery in Manhattan. Shown is the historical thirty-year trailing trend, together with the allegedly "locked in" NOAA predicted trend for 2050. Historical data: NOAA Tides and Current.

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8 UNCERTAINTIES IN CLIMATE CHANGE ATTRIBUTION

Chapter summary

"Attribution" refers to identifying the cause of some aspect of climate change, specifically with reference to anthropogenic activity. There is an ongoing scientific debate around attribution methods, particularly regarding extreme weather events. Attribution is made difficult by high natural variability, the relatively small expected anthropogenic signal, lack of high-quality data, and reliance on deficient climate models. The IPCC has long cautioned that methods to establish causality in climate science are inherently uncertain and ultimately depend on expert judgement.

Substantive criticism of the main IPCC assessments of the role of CO_2 in recent warming focus on inadequate assessment of natural climate variability, uncertainties in measurement of solar variability and in aerosol forcing, and problems in the statistical methods used for attribution.

The IPCC does not make attribution claims for most climate impact drivers related to extreme events. Statements related to statistics of global extremes (*e.g.* event probability or return times, magnitude and frequency) are not generally considered accurate owing to data limitations and are made with low confidence. Attribution of individual extreme weather events is challenging due to their rarity. Conflicting claims about the causes of the 2021 Western North America Heatwave illustrate the perils of hasty attribution claims about individual extreme events.

8.1 Introduction

The Intergovernmental Panel on Climate Change (IPCC) distinguishes between detection of climate change and attribution of its cause. As defined by the AR6 WGI Glossary (IPCC, 2025):

> *Detection*: Detection of change is defined as the process of demonstrating that climate or a system affected by climate has changed in some defined statistical sense, without providing a reason for that change. An identified change is detected in observations if its likelihood of occurrence by chance due to internal variability alone is determined to be small, for example, <10%.
>
> *Attribution:* Attribution is defined as the process of evaluating the relative contributions of multiple causal factors to a change or event with a formal assessment of confidence.

Both detection and attribution rely on statistical analysis. Detection focuses on whether changes are significant enough to stand out from random variation regardless of cause. Attribution involves comparison of observed events to model-generated counterfactuals. Since experimentation on the climate is not possible, attribution requires statistical inference to assess how much human activities (such as GHG emissions) versus natural factors (like volcanic eruptions) contribute to observed changes. Attribution methods assume all external and internal drivers of the system are known and represented.

There are ongoing scientific debates around attribution methods, especially those for attributing extreme weather events to climate change. The IPCC has long cautioned that methods to establish causality in climate science are inherently uncertain and ultimately depend on expert judgement. AR4 Working Group I (Hegerl *et al.*, 2007) explained it as follows:

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> 'Attribution' of causes of climate change is the process of establishing the most likely causes for the detected change with some defined level of confidence... unequivocal attribution would require controlled experimentation with the climate system. Since that is not possible, in practice attribution of anthropogenic climate change is understood to mean demonstration that a detected change is 'consistent with the estimated responses to the given combination of anthropogenic and natural forcing' and 'not consistent with alternative, physically plausible explanations of recent climate change that exclude important elements of the given combination of forcings' (IPCC, 2001)... The approaches used in detection and attribution research described above cannot fully account for all uncertainties, and thus ultimately expert judgement is required to give a calibrated assessment of whether a specific cause is responsible for a given climate change.

AR5 Working Group II (Cramer *et al.*, 2014) makes the following statement:

> Two broad challenges to the detection and attribution of climate change impacts relate to observations and process understanding. On the observational side, high-quality, long-term data relating to natural and human systems and the multiple factors affecting them are rare. In addition, the detection and attribution of climate change impacts requires an understanding of the processes by which climate change, in conjunction with other factors, may affect the system in question.

Because of the complexity of the causal chains in the climate system, investigation of these relationships is exceptionally challenging.

8.2 Attribution methods

The IPCC employs several attribution methods to assess the causes of observed climate changes, distinguishing between natural and human-induced factors. Below is a concise description of the key IPCC attribution methods.

Optimal Fingerprinting uses linear regression to explain variations in observed climate data as a weighted sum of climate model simulations run with and without anthropogenic forcings. The data used in the regression model is weighted to try to minimize the influence of random noise and the estimation method is chosen to account for climate model error.

Time Series Analysis exploits statistical differences between anthropogenic forcing and natural variability to see which dominates observed temperatures and also uses variations in the timing of changes to determine if causal dependence across data series can be inferred.

Process-Based Attribution focuses on understanding the physical mechanisms behind observed changes. This approach combines observations, climate models, and theoretical understanding to attribute changes in specific processes to forcings. This approach is often used for regional climate phenomena, such as monsoon changes or polar amplification

Extreme Event Attribution assesses the role of human influence in the likelihood of occurrence or intensity of extreme weather events (*e.g.* heat waves or droughts). Methods include:

- Probabilistic Event Attribution uses large ensembles of climate model simulations to compare observed events to model-generated counterfactuals
- Storyline Approach examines the physical processes driving an event and evaluates how anthropogenic forcings might have modified those processes

8.3 Attribution of global warming

Attribution statements for global warming in the three most recent IPCC Assessment reports are:

> AR4: **Most of the observed increase** in global average temperatures since the mid-20th century is *very likely* due to the observed increase in anthropogenic greenhouse gas concentrations. (IPCC 2007)
>
> AR5: It is *extremely likely* that **more than half of the observed increase** in global average surface temperature from 1951 to 2010 was caused by the anthropogenic increase in greenhouse gas concentrations and other anthropogenic forcings together. The best estimate of the human- induced contribution to warming is similar to the observed warming over this period. (IPCC 2013)
>
> AR6: The *likely* range of total human-caused global surface temperature increase from 1850–1900 to 2010–2019 is 0.8°C to 1.3°C, with a best estimate of 1.07°C. It is *likely* that well-mixed GHGs contributed a warming of 1.0°C to 2.0°C, other human drivers (principally aerosols) contributed a cooling of 0.0°C to 0.8°C, natural drivers changed global surface temperature by –0.1°C to +0.1°C, and internal variability changed it by –0.2°C to +0.2°C. It is *very likely* that **well-mixed GHGs were the main driver** of tropospheric warming since 1979. (IPCC 2021)

The AR4 and AR5 attribution statements reference the warming since the mid-20th century, the period when greenhouse gas emissions began increasing rapidly. The words "most" and "more than half" are deliberately imprecise, potentially ranging from 51 to 99 percent of the warming – presumably this imprecision is to account for structural uncertainties such as natural internal variability. The confidence level increases from *very likely* to *extremely likely* from AR4 to AR5. The structure of the attribution statement in the AR6 is fundamentally different, referencing the warming to the period 1850-1900. The AR6 attribution statement is more precise numerically, but with a lower level of confidence at "likely" – AR6 attributes essentially all the warming to increases in greenhouse gases. The most confident statement from AR6 relates to the tropospheric warming since 1979, using the words "main driver" and "*very likely*."

There are three areas of substantive criticism of the IPCC's assessment of the causes of the recent warming: inadequate assessment of natural climate variability, inappropriate statistical methods, and substantial discrepancies between models and observations. The last is discussed in Chapter 5, while this chapter discusses the first two factors. All of these criticisms are relevant to the IPCC's policy-informing attribution of the recent warming, which also underpins extreme event attribution

8.3.1 Natural climate variability

AR6 states that natural external drivers since 1850-1900 have changed global surface temperature by –0.1°C to +0.1°C, and internal variability has changed it by –0.2°C to +0.2°C – on average having essentially no net impact on the warming since 1850-1900. As discussed below, this minimal contribution of natural variability has been disputed by several publications that question the magnitudes of solar variability and internal variability from large-scale ocean circulations.

Solar variability

AR5 concluded that the best estimate of radiative forcing due to Total Solar Irradiance (TSI) changes over the period 1750–2011 was very small (0.05 W/m^2, Myrhe *et al.*, 2014). AR6 acknowledges substantially higher values and a much larger range of estimates of changes in TSI over the last several centuries, stating that the TSI between the Maunder Minimum (1645–1715) and the second half of the twentieth century increased by 0.7–2.7 W/m^2, a range that includes both low and high variability TSI data

sets (Gulev, 2021). However, the recommended forcing dataset for the CMIP6 climate model simulations used in AR6 for attribution studies averages two data sets with low solar variability (Matthes, 2017).

While AR6 shows a substantially greater solar impact than does AR5, the overall impact of solar forcing on the climate was still assessed to be small compared to anthropogenic forcing. However, the impact of solar variations on the climate is uncertain and subject to substantial debate (Lockwood, 2012; Connolly *et al.*, 2021) - something that is not evident in the IPCC assessment reports.

The variations of TSI over time remains a challenging problem. Since 1978, there have been direct measurements of TSI from satellites. However, the data exhibits non-negligible inconsistencies, and interpreting any multi-decadal trends in TSI requires comparisons of observations from overlapping satellites. There are several rival composite TSI datasets that disagree as to whether TSI increased or decreased during the period 1986–96 (the ACRIM gap; see Chapter 4). Further, the satellite record of TSI is used to calibrate proxy models that infer past solar variations from sunspots and cosmogenic isotope measurements (Velasco Herrera *et al.*, 2015).

There is substantial evidence for high solar activity in the second half of the 20th century (starting in 1959) and extending into the 1990's, before a decline in the early 21st century; this period is often termed the "Modern Maximum." (Chatzistergos *et al.*, 2023; Solanki *et al.*, 2004; Usoskin *et al.*, 2007). However, some scientists have concluded that it is not possible to be confident of any multi-decadal trend in TSI (Schmutz, 2021).

This uncertainty causes some reconstructions of TSI from 1750 to have low variability (implying a very low impact of solar variations on global mean surface temperature) whereas datasets with high TSI variability can explain more than 70 percent of the temperature variability since preindustrial times (Scafetta, 2013; Stefani, 2021). The choice of TSI satellite record used in an analysis can therefore substantially influence how much climate change is attributed to human versus natural forcings.

There is growing evidence that other aspects of solar variability, which are referred to as solar indirect effects, either amplify TSI forcing or are independent of TSI forcing. Scafetta *et al.* (2023) suggests that ~80 percent of solar influence on climate might stem from non-TSI mechanisms. There are numerous candidate processes, including solar ultraviolet changes; energetic particle precipitation; atmospheric-electric-field effect on cloud cover; cloud changes produced by solar-modulated galactic cosmic rays; large relative changes in the magnetic field; and the strength of the solar wind. Such solar indirect effects are not included in climate models, although indirect methods of estimating their impacts suggest they are significant. However, claims of non-TSI mechanisms influencing climate are uncertain and debated.

Natural variability of large-scale ocean circulations

Variations in global mean surface temperature are linked to recurrent large-scale variations in ocean circulation patterns, including the Atlantic Multidecadal Oscillation (AMO), the Pacific Decadal Oscillation (PDO) and the El Nino-Southern Oscillation (ENSO). These circulations influence ocean heat uptake and heat distribution and also influence atmospheric circulation patterns and cloud distributions. There is some debate as to whether these variations are strictly internal to the climate system, or whether this variability can have a solar/astronomical origin or can be influenced by large volcanic eruptions.

While climate models simulate the large-scale ocean circulations and internal climate variability, most models have too little amplitude compared to observations at multi-decadal frequencies and phasing out-of-sync with the observed climate (Kravtsov *et al.* 2024). Averaging multiple simulations effectively averages out the internal variations, leaving only the forced climate variability (*e.g.* CO_2 forcing). With most of the modern warming beginning in the late 1970's, the recent 50-year warming is on the same time scale as the multi-decadal oscillations of the AMO and PDO.

Here are summary statements from the AR5 and AR6 reports:

> AR5: Decadal variability in the Pacific, associated with the PDO or IPO [Interdecadal Pacific Oscillation], contributes significantly to regional and global temperature trends, but the relative contributions of internal variability and external forcing are difficult to disentangle in CMIP5 simulations.
>
> AR6: Since AR5, there has been increased understanding of the role of internal variability, such as ENSO, PDO, and AMO, in modulating regional climate trends. However, limitations in simulating the exact timing and amplitude of these modes in CMIP6 models contribute to uncertainties in attributing observed changes to anthropogenic forcing (*high confidence*).

The amplitude of the peak-to-trough impact of the multi-decadal oscillations on global temperatures has been assessed by the IPCC AR6: "The likely range of change due to internal variability is -0.2°C to +0.2°C (IPCC, 2021)." This implies a trough-to-peak change of 0.4°C. Over many centuries, any global temperature changes from the troughs and peaks will cancel out, with little to no net impact.

However, with a nominal timescale of 60-80 years for oscillations such as the AMO and PDO, the timing of the peaks and troughs can be confused with the secular trend. This becomes very relevant for attributing the warming for the past 50 years, when most of the recent warming has occurred. Even if climate models have the correct amplitude of the multidecadal oscillations, the timing of the peaks and troughs is not adequately simulated, with each model and individual ensemble simulating a different phasing. Once the simulations of the ensemble members and different models are averaged, the natural internal variability contribution is averaged out owing to differences in phasing, effectively cancelling the role of natural internal variability in the attribution process.

The time series of global surface temperature anomalies since 1850 (Figure 8.1) shows irregular variations of significant amplitude against the background of an overall warming trend and, after 1976, a pronounced difference in trends between the Northern Hemisphere and the Southern Hemisphere. The period between 1905-1945 shows a strong trend of warming. The following 30 years from 1945-1976 showed slightly declining temperatures. The most recent warming period started in 1977.

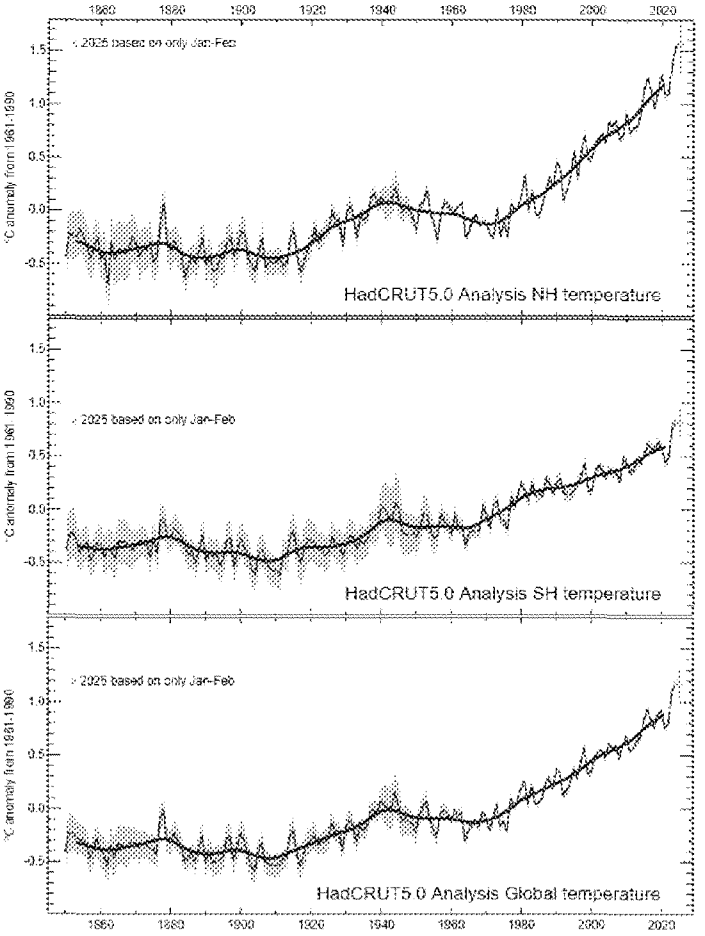

Figure 8.1 Global average surface temperature anomalies 1850—2025. Top: Northern hemisphere. Middle: Southern hemisphere. Bottom: Global average. Source: UK Hadley Centre https://crudata.uea.ac.uk/cru/data/temperature/HadCRUT5.0Analysis.pdf

The causes of the early 20th century warming are discussed by Hegerl *et al.* (2017; 2019). The atmospheric CO_2 concentration increased from 298 ppm in 1905 to 310 ppm in 1941, implying that CO_2 had little impact. Volcanic activity during this period was very low, and solar forcing is uncertain. Yet Hegerl *et al.* (2017) somehow inferred that 40-54 percent of this warming could be attributed to external forcing, with the rest associated with internal variability. Bronniman *et al.* (2024) focused on the causes of the cooling in the first decade of the 20th century in the Southern Hemisphere. They found that the cooling was related to a La-Niña-like pattern in the Pacific, a cold tropical and subtropical South Atlantic, a cold extratropical South Pacific, and cool southern midlatitude land areas. The Southern Annular Mode was positive, with a strengthened Amundsen–Bellingshausen seas low, although the spread of the data products is considerable.

The warming in the 1930's and subsequent cooling during mid-century was particularly pronounced in the Arctic. Bokuchava and Semenov (2021) find that these variations were most likely caused by a combined effect of long-term natural climate variations in the North Atlantic and North Pacific with a contribution of the natural radiative forcing related to the reduced volcanic activity and variations of solar activity, as well as growing greenhouse gases concentrations. Tokinaga *et al.* (2017) showed that the combined effect of internally generated Pacific and Atlantic interdecadal variability intensified Arctic

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warming in the early 20th century. The synchronized Pacific-Atlantic warming drastically alters planetary-scale circulations over the Northern Hemisphere; these same circulation patterns have a global influence.

The cooling period between 1945 and 1976 has been referred to as the "grand hiatus." Numerous causes have been hypothesized: natural internal variability from fluctuations associated with the Pacific Decadal Oscillation and Atlantic Multidecadal Oscillation; cooling from increased emissions of aerosols from industrial activities; increased heat uptake in the Atlantic, Southern and Equatorial Pacific Oceans. Thompson *et al.* (2010) find that that the hemispheric differences in temperature trends in the middle of the twentieth century stem largely from a rapid drop in Northern Hemisphere sea surface temperatures of about 0.3 °C between about 1968 and 1972.

The Great Pacific Climate Shift of 1976-1977 was a notable climatic event characterized by an abrupt change in the North Pacific Ocean's atmosphere-ocean system that interacted with global climate patterns. This shift is closely associated with the Pacific Decadal Oscillation (PDO) that oscillates between warm and cool phases over decades. The 1976 shift marked a transition from a predominantly negative (cool) PDO phase (1947–1976) to a positive (warm) phase (1977 through 2000), with significant implications for global and regional climate patterns, including the frequencies of El Nino and La Nina events. The Great Pacific Climate Shift coincided with the beginning of a period of accelerated global warming. When the Great Pacific Climate Shift is accounted for in climate attribution analyses since 1950, 40 percent or more of the warming in the second half of the 20th century is attributed to natural internal variability (McLean *et al.*, 2009; Tung and Zhou, 2013; Chylek *et al.*, 2016; Scafetta, 2021).

8.3.2 Optimal fingerprinting

Optimal fingerprinting is a statistical technique introduced by Allen and Tett (1999) that compares observed climate data to climate model simulations to identify patterns (or "fingerprints") associated with human or natural forcing. It involves taking a vector of observed climate changes, such as warming rates in locations around the world, and decomposing them into a weighted sum of "signals", which are analogues to the observations generated by climate models with different types of forcings. The weights are chosen using a regression method called Total Least Squares (TLS). The analysis commonly uses just two signals, one generated by models using only anthropogenic forcings and one using only natural forcings. If the estimated weighting coefficient attached to a signal is significantly different from zero, then that signal is said to be "detected". If it is close to 1.0, then the model generating the signal is said to be consistent with observations. If it is less than 1.0, then the model signal for that forcing is too strong and needs to be scaled down, and vice-versa. Both the observed data and the signals are weighted using a model-generated estimate of patterns of randomness in the climate system so as, in principle, to put maximum weight on regions where natural variability is minimized.

Optimal fingerprinting is the primary tool for attribution in the research literature. While it has been widely used and prominently featured by the IPCC since 2001, there is very little literature examining the statistical properties of the results it generates. One of its inherent weaknesses is that results depend on assumptions about the accuracy of climate models, especially regarding their representation of natural variability (IPCC AR5 Ch 10.2.3).

A series of papers by McKitrick (McKitrick 2021, 2022, 2023, 2025) has challenged the optimal fingerprinting method, arguing that it is inherently unreliable and that practices adopted from econometrics can provide more valid results. Statistical theory requires that for regression models to yield unbiased coefficients, a set of assumptions called the Gauss-Markov conditions must hold. McKitrick (2021) argued that the Allen and Tett (1999) methodology violates the Gauss-Markov conditions, leading to potentially biased and inconsistent fingerprinting coefficients, undermining the reliability of the method. Chen *et al.* (2023) confirmed this analysis, although they argued that the method could yield valid results under very stringent assumptions. McKitrick (2022) and (2023) raised a further concern that climate scientists—virtually alone among

scientific disciplines—have used TLS to estimate anthropogenic greenhouse gas signal coefficients, despite its tendency to be unstable unless some strong assumptions hold that in practice are unlikely to be true. Under conditions that easily arise in optimal fingerprinting, TLS estimates have a large positive bias. Thus, any study that used TLS for optimal fingerprinting without verifying its applicability in the specific data context has likely overstated the attribution.

McKitrick (2025) presented an empirical example comparing the results of conventional optimal fingerprinting against methods drawn from mainstream econometrics that are known to be valid for the specific application of signal detection. While the IPCC optimal fingerprinting method yields an anthropogenic signal coefficient close to 1.0 on a global temperature data set spanning 1900 to 2010, consistent estimation yields a coefficient around 0.4, which rises to about 0.65 on data spanning 1980 to 2010, implying the model response to greenhouse gases needs to be scaled down by about half to optimally match observations. The natural forcing signal coefficient, by contrast, is between 2.0 and 4.0, implying the climate model signals of natural forcing need to be scaled up two-to four-fold to match observed climate change. The fingerprinting coefficients estimated in McKitrick (2025), when used to scale the average sensitivity of the climate models used to generate the forcing signals in his data set, imply a Transient Climate Sensitivity of 1.4°C, which is consistent with the estimate by Lewis (2023) using a different estimation method and multiple independent data sets.

While these analyses do not falsify results of the IPCC optimal fingerprinting method, they do challenge the basis on which they were believed to be correct.

8.3.3 Time series methods

The IPCC (AR5 WGI 10.2.2) drew attention to alternative approaches of assessing causality that emerged from the time series econometrics literature. These have the advantage of not depending on assumptions about the accuracy of climate models, but the disadvantage that they depend on difficult-to-test assumptions about the data generating process underlying climate and forcing data. The methods, now referred to as climate econometrics, use the tools of unit root testing, Granger causality and cointegration analysis, all of which are familiar in economics and finance and which are slowly being adopted in climate science. Time series analysis methods hold out the possibility of determining whether anthropogenic or natural forcings are the primary drivers of climate change without requiring the use of climate models, although key questions remain unsettled (e.g. Dergiades *et al.*, 2016, Balcombe *et al.*, 2019, Dagsvik *et al.*, 2020, Razzak, 2022, Dagsvik and Moen, 2023).

"Granger causality" modeling is a tool for determining directions of influence in data series that move together. It is a statistical, not a physical, concept. If knowing the current value of one variable significantly improves the forecast accuracy of another variable, we can infer a causal connection exists; this is called Granger causality. The modeling tools, called vector autoregression, measure direct impulse-response patterns and feedbacks. An application to the well-known Vostok ice core data revealed an error in Al Gore's documentary *An Inconvenient Truth*. Gore showed the data and drew attention to the coherence of temperature and CO_2 changes over a 440,000 year span, which he asserted was due to CO_2 driving temperature changes. But temperature changes can also affect atmospheric CO_2 levels. Davidson *et al.* (2015) examined the series and found that temperature Granger causes CO_2 but not the reverse. In other words on the time scales represented in the Vostok data, the coherence in the series is primarily due to the influence of temperature on CO_2 levels, not the feedback of CO_2 levels on temperature.

In summary, the primary statistical methods for attributing causation in climate data are optimal fingerprinting and time series analysis. Applications of the Allen and Tett (1999) optimal fingerprinting method dominate the attribution literature and have underpinned past IPCC conclusions, but results depend on the accuracy of climate models and the method has recently been criticized as inherently biased. Time

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series methods do not depend on climate models but require assumptions of their own and have generated results that have thus far not converged on a consensus.

8.4 Declining planetary albedo and recent record warmth

A sharp recent increase in global average temperatures has raised the question of short-term drivers of climate. One such candidate is the fraction of absorbed solar radiation which has also increased abruptly in recent years. The question is whether the change is an internal feedback to warming caused by greenhouse gases, or whether something else increased the fraction of absorbed radiation which then caused the recent warming.

The planetary albedo is the fraction of incoming solar radiation that is reflected back into space rather than being absorbed by the planet. Highly reflective surfaces like cloud tops and snow and ice are most important in this regard. The Earth's albedo is approximately 30 percent, meaning almost a third of the sunlight that reaches Earth is directly reflected back to space. A lower albedo implies more solar energy is absorbed by the planet to be then re-radiated as heat. Hence, other things being equal, a decline in planetary albedo is associated with a warming of the Earth.

Arguably the most striking change in the Earth's climate system during the 21st century is a significant reduction in planetary albedo since 2015, which has coincided with at least two years of record global warmth. Figure 8.2 shows the planetary albedo variations since 2000, when there are good satellite observations. The 0.5 percent reduction in planetary albedo since 2015 corresponds to an increase of 1.7 W/m^2 in absorbed solar radiation averaged over the planet (Hansen and Karecha, 2025). For comparison, the IPCC estimate of forcing from the increase in atmospheric CO_2 compared to preindustrial times is approximately 2.2 W/m^2 (Figure 3.1.2).

Looking back prior to 2000 with less adequate data, Goessling *et al.* (2025) assessed that the planetary albedo was relatively low around the 1940's and 50's before rising industrial aerosol precursor emissions increased the albedo until the 1980's. The strongest planetary albedo excursions were high-albedo episodes caused by volcanic eruptions, such as after the Mount Pinatubo eruption in 1991. Although uncertain, the 2023 planetary albedo minimum might have been the lowest since at least 1940.

Changes in surface characteristics cannot explain this decrease in planetary albedo since 2015:

- Arctic sea ice extent has declined by about 5 percent since 1980 (https://nsidc.org/data/seaice_index/images/s_plot_hires.png), although following 2007 there has been a pause in the Arctic sea ice decline (England *et al.*, 2025)
- Regarding Antarctic sea ice, the IPCC AR6 concludes that "There has been no significant trend in Antarctic sea ice area from 1979 to 2020 due to regionally opposing trends and large internal variability." (Summary for Policymakers, A.1.5)
- Northern hemispheric annual snow cover has been slowly declining since 1967, with barely significant trends. The data show the Northern Hemisphere has snowier winters, accompanied by more rapid melt in spring and summer, see http://climate.rutgers.edu/snowcover/ and Section 5.6
- Global greening (Chapter 2) is contributing to the decrease in planetary albedo, as forests have a lower albedo than open lands or snow. However, there is some evidence that forests increase cloud cover (high reflectivity), which counteracts the direct albedo decrease associated with increasing forested area.

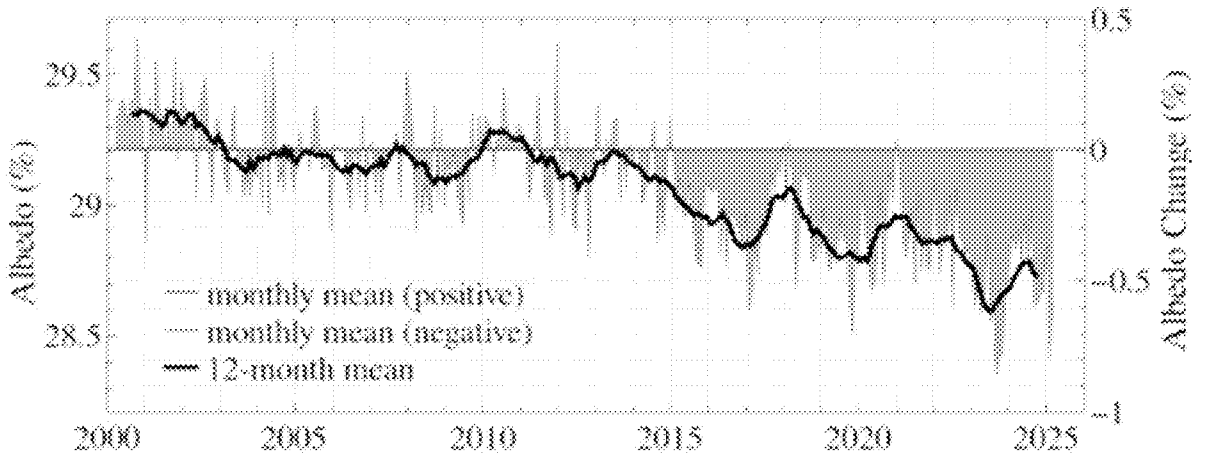

Figure 8.2. Earth's albedo (reflectivity, in percent), with seasonality removed. From Hansen and Karecha (2025)

Changes in surface reflectivity are contributing to a small, slow decline in planetary albedo. However, these changes cannot explain the sharp decline in planetary albedo beginning in 2015. Further, any changes in surface albedo are effectively damped by about a factor of three on average, primarily due to cloud masking (Loeb *et al.* 2019). Surface albedo changes have thus contributed only weakly to the recent planetary albedo decline, particularly when averaged annually and globally. This leaves the most likely explanation for the sharp albedo decline as changes in atmospheric aerosols and/or clouds.

Aerosols are small particles in the atmosphere that reflect sunlight and can interact with cloud processes to make the clouds more reflective. Aerosols have both natural origins (*e.g.* dust from soils, wildfires) as well as human origins from combustion (including fossil fuels). Regions that are greening and/or have an increase in rainfall might produce less dust. For anthropogenic aerosols, new ship fuel regulations aimed at reducing sulfur emissions were implemented in three phases, in 2010, 2015 and 2020. Sulfate particles reflect solar radiation. Cleaner air means less solar radiation is reflected, which contributes to surface warming. Indirect effects of sulfate aerosols include increasing the reflectivity of low-level clouds in the subtropics. There is controversy surrounding the importance of this change in sulfate emissions to the Earth's radiation balance (Hodnebrog *et al.*, 2024; Yuan *et al.*, 2024), but the restriction of this effect to major shipping routes suggests a small global impact (Schmidt, 2024).

Changes in clouds are the primary candidate to explain the decline in global albedo since 2015. Two recent papers (Loeb *et al.*, 2024; Goessling et al 2024) have addressed recent variations in cloud properties. By considering satellite and reanalysis data, Loeb *et al.* found that decreases in low- and mid-level clouds since 2015 are the primary reason for decreasing planetary albedo in the Northern hemisphere, whereas in the Southern hemisphere the decrease in planetary albedo is primarily due to decreases in mid-level clouds across all latitude zones. Goessling *et al.* (2024) found that cloud anomalies were mainly due to reduced low-level clouds. Regions with coherent low-level cloud reductions over the past decade include the warm pool region around the Maritime Continent and the northern extratropical western Pacific, as well as large parts of the Atlantic and adjacent land regions. The reduction of global cloud cover identified in these analyses since 2015 is 1-2 percent.

The issue then becomes the cause of the change in cloud cover. Two explanations have been posited for the declining cloud cover over the past decade:

- Natural climate variability

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- Changes in low cloud cover associated with warming sea surface temperatures, implying an emerging positive feedback to climate change (Hansen and Karecha, 2025)

It is not easy to justify a new positive low cloud feedback that began emerging in 2015. However, there are numerous natural climate signals during this period that are associated with atmospheric circulation changes that can influence the distribution of clouds:

- The 2014-2016 was one of the strongest El Niño events on record
- A cold anomaly beginning in 2015 in the subpolar gyre of the North Atlantic reflects a shift in the ocean circulation pattern associated with decadal variability in the Atlantic (Frajka-Williams *et al.*, 2017; Arthun *et al.* 2021).
- The Pacific Decadal Oscillation positive index peaked in 2016, then declined and has been in negative territory since late 2019
- Eruption of the submarine Hunga-Tonga volcano in 2022

Interannual cloud anomalies associated with the El Niño Southern Oscillation (ENSO) have a significant global signal and strong regional signals, especially over the tropical Indian and Pacific Oceans.

The Hunga Tonga eruption is remarkable in its coincidence with the exceptionally low value of planetary albedo in 2023. Goessling *et al.* (2024) found that the cloud perturbations in 2023 showed a different pattern from the overall pattern since 2015, with reduced cloud cover being most pronounced in the northern hemisphere and tropics. Regional reductions in cloud cover were most pronounced over the eastern Indian Ocean, over South America and extending over the eastern Pacific, as well as over northern North America, in the Southern Ocean around 60S, in the subtropical and eastern North Atlantic, and in parts of the North Pacific.

The Hunga Tonga eruption was unusual in that it injected large amounts of water vapor into the stratosphere in addition to sulfate particles. Early publications focused on the impacts to stratospheric circulations and the direct radiative impact. In 2025, papers are emerging that examine the indirect effects of Hunga Tonga on surface climate using ensemble simulations from earth system models (Bednarz *et al.*, 2025; Kuchar *et al.*, 2025). These papers found statistically significant impacts on regional climates that were driven by circulation changes from couplings between the stratosphere and troposphere. These papers indicate the complex interactions between volcanic activity and climate dynamics. More research is needed to untangle any impacts of the Hunga Tonga eruption on the planetary albedo.

In summary, the decline in planetary albedo and the concurrent decline in cloudiness have emphasized the importance of clouds and their variations to global climate variability and change. A change of 1- 2 percent in global cloud cover has a greater radiative impact on the climate than the direct radiative effect of doubling CO_2. While it is difficult to untangle causes of the recent trend, the competing explanations for the cause of the declining cloud cover have substantial implications for assessing the Equilibrium Climate Sensitivity and for the attribution of the recent warming. An additional 10 years of data should help clarify whether this is a strong positive cloud feedback associated with warming or a temporary fluctuation driven by natural variability

8.5 Attribution of climate impact drivers

The IPCC (Ranasinghe *et al.* 2021) defines "climate impact drivers" or CIDs as "physical climate system conditions (e.g., means, events, extremes) that affect an element of society or ecosystems." Hence CIDs are those features of the weather and climate system of primary interest in assessing the impacts of climate change since they potentially affect humans and the natural world. For instance, under the heading "Heat and Cold," CIDs are identified as mean air temperature, extreme heat, cold spells and frost. The IPCC

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also points out that CIDs are not necessarily harm-related: depending on the system in question they can be detrimental, neutral, beneficial or a combination.

The first columns Table 12.12 in Ranasinghe *et al.* (2021, p. 1856), reproduced here as Table 8.1, summarize the AR6 assessment of whether a signal of attributable anthropogenic influence has emerged across all major CIDs. One of the themes of this chapter is that attribution methods used by the IPCC tend to overstate the anthropogenic influence and understate the role of natural variability. Nonetheless a striking feature of that summary table is how few CIDs exhibit an anthropogenic signal sufficient to distinguish them from natural variability.

Out of the 33 weather impact categories listed, an anthropogenic signal is asserted with *high confidence* in only five, and with *medium confidence* in a further four. (Note that one of the CIDs is an increase in CO_2 levels, and since it is a tautology to attribute this to increased CO_2 levels this CID can be ignored.) For the rest the IPCC does not claim to have detected anthropogenic drivers. Of the five *high confidence assertions*, two are for changes in average temperatures (air and ocean) hence are not measures of extreme weather. Further, two of the four *medium confidence* assertions are related to ocean chemistry and thus are likewise not related to extreme weather. The IPCC does not assert a human influence on many non-temperature weather features such as wind, precipitation, flooding, or drought.

Other columns of IPCC Table 12.12 report on whether anthropogenic signals are expected to emerge this century under RCP8.5, the most extreme forcing scenario. We have omitted these columns for several reasons. First, because they refer to whether climate models project detectable signals in the observations, which is a very different question than our concern here: whether a signal has been detected in historical data. Second, as we discuss in Chapter 4, the RCP8.5 scenario is a misleading and implausible high-end storyline, it is not a "base case" or business-as-usual projection. Third, the ensemble of detailed models is acknowledged (Palmer and Stevens 2019) to be "not fit for purpose" in describing regional changes and "unable to represent future conditions at the degree of spatial, temporal, and probabilistic precision with which projections are often provided." (Nissan et al, 2019). Even with these caveats, we note that the omitted columns in AR6 Table 12.12 show most weather impacts are not expected to exhibit an anthropogenic signal through the end of this century.

Climatic Impact-driver Type	Climatic Impact-driver Category	Already Emerged in Historical Period
Heat and Cold	Mean air temperature	3
	Extreme heat	2
	Cold spell	4
	Frost	
Wet and Dry	Mean precipitation	
	River flood	
	Heavy precipitation and pluvial flood	
	Landslide	
	Aridity	
	Hydrological drought	
	Agricultural and ecological drought	
	Fire weather	
Wind	Mean wind speed	
	Severe wind storm	
	Tropical cyclone	
	Sand and dust storm	
Snow and Ice	Snow, glacier and ice sheet	
	Permafrost	
	Lake, river and sea ice	11
	Heavy snowfall and ice storm	
	Hail	
	Snow avalanche	
Coastal	Relative sea level	
	Coastal flood	
	Coastal erosion	
Open Ocean	Mean ocean temperature	
	Marine heatwave	
	Ocean acidity	
	Ocean salinity	13
	Dissolved oxygen	14
Other	Air pollution weather	
	Atmospheric CO_2 at surface	
	Radiation at surface	

High confidence of decrease | Medium confidence of decrease | Low confidence in direction of change | Medium confidence of increase | High confidence of increase

Table 8.1: Reproduction of column 1 of Table 12.12, IPCC AR6 Working Group I report. Emergence of anthropogenic signal in historical period for CIDs shown. White: no signal detected. Blue and orange: change detected (decrease or increase) and confidence level as indicated in color legend.

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As discussed in Chapter 6 natural variability dominates patterns of extreme weather systems and simplistic assertions of trend detection are frequently undermined by regional heterogeneity and trend reversals over time. Table 8.1 makes the related point that it is not currently possible to attribute changes in most extreme weather types to human influences. Taking wind as an example, the IPCC claims that an anthropogenic signal has not emerged in average wind speeds, severe windstorms, tropical cyclones or sand and dust storms, nor is one expected to emerge this century even under an extreme emissions scenario. The same applies to drought and fire weather.

8.6 Extreme event attribution (EEA)

Examining the IPCC's treatment of extreme weather and climate event attribution more broadly, AR6 provides an ambiguous assessment of the role of anthropogenic warming that differs between its chapters. Chapter 11 of WG1 states (Seneviratne *et al.*, 2021):

> Evidence of observed changes in extremes and their attribution to human influence (including greenhouse gas and aerosol emissions and land-use changes) has strengthened since AR5, in particular for extreme precipitation, droughts, tropical cyclones and compound extremes (including dry/hot events and fire weather). Some recent hot extreme events would have been extremely unlikely to occur without human influence on the climate system.

By contrast, as noted in Section 8.5, Chapter 12 of WG1 (Table12.12) paints a different picture – presumably, the expert judgment of different groups of authors for the two chapters came to different conclusions (Ranasinghe, 2021):

- High confidence in an increase in extreme heat events in tropical regions where observations allow trend estimation and in most regions in the mid-latitudes, medium confidence elsewhere
- Medium confidence in a decrease in extreme cold events in Australia, Africa and most of northern South America where observations allow trend estimation
- No evidence of emergence in the historical period of a change in river floods, heavy precipitation, drought, fire weather, severe wind storms, and tropical cyclones

While the overall issue of detecting changes in extreme weather events and their attribution remains ambiguous, most of the activity in this area relates to the attribution of particular extreme weather events. The most prominent effort is World Weather Attribution (WWA; worldweatherattribution.org), an international research initiative for extreme event attribution that purports to analyze how climate change influences the likelihood and intensity of extreme weather events. Their approach is to use large ensembles of regional climate models to compare an event in today's climate with one in a counterfactual pre-industrial climate without human influences.

WWA has a prominent public presence in linking extreme weather to climate change, with its press releases attracting considerable attention in public and policy discussions. However, the WWA's extensive promotion of non-peer-reviewed findings, its open admission to shaping analyses to serve litigation, and its methodological challenges have sparked controversies, with critics questioning the robustness and impartiality of their conclusions (Pielke Jr. 2024). Despite these issues, WWA's work continues to influence climate science and media narratives. Technical criticisms of the approach include a lack of a formal detection process; an implicit assumption that 100 percent of the post-industrial warming is caused by greenhouse gases; and a failure to adequately account for internal climate variability.

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Because EEA is relatively new, many basic methodological issues have yet to be settled in the expert literature. An important challenge is the lack of data. Extreme events are by definition rare. Many analyses of extreme event types (including the U.S. National Assessment Reports) only evaluate data since 1950 or 1970. However, as emphasized by Chapter 6, many of the worst extreme weather and climate events in U.S. history occurred in the first half of the 20th century, including in the early 19th century. And if paleoclimate reconstructions are considered, it becomes very difficult for an event to pass thresholds of what is expected from natural variability, particularly if a reasonably sized geographic region is considered.

Another challenge is defining the event under study. There is a longstanding literature in statistics and econometrics on the challenge of analyzing data with outliers. The issue arises because a data series establishes a probability distribution defining the expected range of observations. If an outlier is observed it might indicate that the underlying process giving rise to the data distribution has changed (which in the weather context would mean that a climate change has been detected) or that the underlying process has multiple regimes each with a different probability distribution, in which case observing an outlier simply means we were temporarily in a different regime, but the system itself was unchanged. If a time series contains only a single outlier event at the end of the series it is not possible to determine which model is the correct one (Chen and Liu 1993). For instance, there might be an "ordinary" weather regime that yields a distribution of summer daytime highs in a particular coastal region, and a second "heatwave" regime that kicks in when an inland blocking event occurs, which yields a temperature distribution centered 15°C higher than the first one. A day with temperatures 13°C above normal would either be an extreme heat anomaly under the first regime or a somewhat cool event under the second, and we have no way in this case of knowing on statistical grounds which view is correct.

Visser and Petersen (2012) and Sardeshmukh *et al.* (2015) both point out that different distributions might fit observed data equally well but yield very different implications about the likelihood of a specific weather event. Visser and Petersen argue that, in view of the deep uncertainties of extreme weather analysis, drawing a connection between individual events and global climate change should be avoided. Furthermore, the existence of an outlier at the end of a data series poses the problem that estimates of the event probabilities will be biased whether the outlier is included or excluded (Barlow *et al.*, 2020). Methods to eliminate the bias have not yet been established, leading some experts (*e.g.* Miralles and Davison 2023) to argue that in settings in which a data series contains a single extreme event at the end, estimation of a return period for the extreme event will be so biased and uncertain that it should be avoided altogether.

We provide a case study of a recent high impact extreme event in the U.S. to illustrate the challenges and ambiguities in attributing the frequency and intensity of extreme weather events to human-caused warming.

8.6.1 Case study – 2021 Western North America heat wave

The 2021 Western North America heat wave was an extreme event that affected much of Western North America in late June 2021. Surface temperature records were set in Portland, OR (116°F; previous record 107°F) and Seattle, WA (108 °F; previous record 103°F) (Mass *et al.*, 2024).

The WWA team generated international headlines with their analysis, which provided the following attribution statements (WWA, 2021; Philip *et al.*, 2022):

- Based on observations and modeling, the occurrence of this heatwave was virtually impossible without human-caused climate change.
- The event is estimated to be about a one in 1000-year event in today's climate.
- The event would have been at least 150 times rarer without human-induced climate change.
- This heatwave was about 2°C hotter than it would have been if it had occurred at the beginning of the industrial revolution (when global mean temperatures were 1.2°C cooler than today).

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But an important counter to the first claim is that other researchers concluded from historical weather data that while a heat wave of the magnitude observed was indeed virtually impossible without anthropogenic climate change, it was also virtually impossible *with* climate change. Bercos-Hickey (2022) noted "these temperatures were virtually impossible under any previously experienced meteorological conditions, with or without global warming." McKinnon and Simpson (2022) stated "the most likely explanation remains that the weather event itself was 'bad luck.'" The 2023 Oregon Climate Assessment (Fleischman, 2023) concluded that the heat dome would have formed even without climate change and "There is no evidence that the highly unusual combination of weather features that drove the heat dome were made more likely by climate change, and climate models do not project an increase in the frequency of high-pressure ridges over the Pacific Northwest" (Fleischman, 2023, p. 49).

Mass *et al.* (2024) summarizes the proximate sequence of compound events leading to the heat wave. There was a record-breaking mid-tropospheric ridge over the Pacific Northwest, forced by a tropical disturbance in the western Pacific. This produced record-breaking mid-tropospheric temperatures, strong subsidence in the lower atmosphere, low-level easterly flow that produced downslope warming on regional terrain and the removal of cooler marine air, and an approaching low-level trough that enhanced downslope flow. The event occurred at a time of maximum solar insolation, and drier-than-normal soil moisture. Using a storyline approach, Mass *et al.* assessed that there was no trend in drought and dry soils in the Pacific Northwest; there is no evidence of global warming producing stronger ridges of high pressure, and no observed trend in heat waves or record temperatures in the region. They concluded that although anthropogenic warming might have contributed as much as 2°F to the magnitude of the event, there is little evidence of further amplification of the event from increasing greenhouse gases.

Bercos-Hickey *et al.* (2022) conducted a statistical analysis of a model-based attribution study of this heat wave. Because the event is a far outlier and far above the bounds of Generalized Extreme Value distributions fitted from historical data, they concluded that estimates of return times, quantitative changes in event magnitude and frequency, and probability of the extreme temperatures such as provided by the WWA are not accurate and should be interpreted as having low confidence. They found that hindcast attribution methods using an ensemble of regional climate models, combined with Pearl (2009) causal inferences, can provide limited and conditional information about the magnitude of the human influence on this heatwave - they provided a more highly constrained estimate that human activities caused a ~1.4°F–1.8°F increase in the daily maximum temperatures.

Zeder *et al.* (2023) also concluded that the methods employed by Philip *et al.* (2022, the WWA analysis) tend to overstate the rarity of extreme heat waves, leading to a biased perception of the effect of climate change on the heatwave event: "The tendency to overestimate the return period of observed extreme heatwave events may fuel the impression that seemingly impossible heatwave extremes are currently clustering at an unprecedented rate."

The 2021 Western North America heatwave was a rare and unprecedented compound weather event that broke century-old temperature records by as much as 9°F. While the WWA team received worldwide publicity for their rapid attribution claims blaming anthropogenic climate change, subsequent peer-reviewed analyses showed that the event was caused by rare meteorological conditions that were not made more probable by global warming.

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PART III: IMPACTS ON ECOSYSTEMS AND SOCIETY

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9 CLIMATE CHANGE AND U.S. AGRICULTURE

Chapter summary

There has been abundant evidence going back decades that rising CO_2 levels benefit plants, including agricultural crops, and that CO_2-induced warming will be a net benefit to U.S. agriculture. The increase in ambient CO_2 has also boosted productivity of all major U.S. crop types. Various attempts to argue that CO_2-induced warming will harm agriculture do not hold up under scrutiny.

9.1 Econometric analyses

Econometric analyses of the effects of climate change on agriculture have sought to integrate information about long term crop yield changes in response to temperature and precipitation changes under assumptions about adaptive behavior by farmers. One method focuses on variations in agricultural land values. The rationale is that if climate change is a long-term net benefit for agriculture it should be capitalized into higher market values for agricultural land, and vice versa. While individual crops might benefit from, or be harmed by, climate change, once the adaptative responses of farmers are considered the value of farmland represents an index of whether the changes are expected to be beneficial or not. Mendelsohn *et al.* (1994) examined the relationship between historical climatic variations on agricultural land values and concluded global warming would be slightly beneficial to American agriculture.

The Mendelsohn *et al.* method, called Ricardian analysis after David Ricardo, the 19th century British economist who pioneered the study of land values, attracted subsequent criticism from authors who argued it failed to account for differences in land values attributable to fixed locational characteristics like soil quality, and non-climatic changes including nearby urbanization. Deschênes and Greenstone (2007) looked at agricultural profits instead of land values and reached conclusions similar to Mendelsohn *et al.* (1994), namely that past climatic variations had relatively little effect on farm profitability and that warming would likely yield small overall benefits for the U.S. agricultural sector. However, a subsequent exchange with critics led them (Deschênes and Greenstone 2012) to revise their conclusions and project potentially large losses in U.S. agriculture due to climate warming.

Burke and Emerick (2016) looked at temperature variations over 1980 to 2000 and argued that farmers were not as able to adapt to temperature changes as the Ricardian method assumes and that climate change would have large negative impacts on corn and soy yields. Schlenker and Roberts (2009) similarly argued that yield gains to past warming would not carry over to the future and corn and soy yields would sharply decrease this century due to climate change.

Two recent studies have argued that pessimistic findings such as these are not robust. Ortiz-Bobea (2019) argued that land values aggregate farm and non-farm influences and the latter need to be filtered out. He developed a data set using cash rents for agricultural activity as a measure of land value specifically for farming activity. Whereas the land value model implied future losses under climate warming, the same model estimated using cash rents did not, leading the author to conclude the pessimistic results were due to using an inaccurate measure of the returns to farming activity. Bareille and Chakir (2023) assembled a large data base on farm sale prices in France for properties that sold twice between 1996 and 2019. They could replicate pessimistic results showing negative effects of warming on agricultural land values using conventional econometric modeling. But by taking advantage of the repeat sales data, which provides information on site-specific changes in land prices, they found the results reversed and implied that climate change will be very beneficial for French agriculture. The authors concluded that, taking adaptation into account, a warming climate would yield positive benefits for French agriculture that were between two and

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20 times larger than had previously been estimated. On average, with full adaptation, they concluded that climate changes under the medium RCP4.5 scenario could double the value of French farmland by 2100.

A major deficiency of all these studies, however, is that they omit the role of CO_2 fertilization. Climate change as it relates to this report is caused by GHG emissions, chiefly CO_2. The econometric analyses referenced above focus only on temperature and precipitation changes and do not take account of the beneficial growth effect of the additional CO_2 that drives them. As explained in Chapter 2, CO_2 is a major driver of plant growth, so this omission biases the analysis towards underestimation of the benefits of climate change to agriculture.

9.2 Field studies of CO_2 enrichment

One of the ways the effect of CO_2 on crop growth has been studied is through "free air enrichment experiments" or FACE plots, in which small sources of CO_2 are placed in fields surrounding plants and the growth response to elevated CO_2 under varying weather conditions are recorded. Ainsworth *et al.* (2020) summarizes results from about 250 such studies. They found that elevation of CO_2 by 200 ppm caused an average 18 percent increase in crop yield in C3 plants. C4 plants exhibited benefits mainly under drought conditions.

In addition to FACE plot experiments there have been thousands of laboratory experiments on the effects of CO_2 on all kinds of plant growth. Here we review some of the results on key U.S. agricultural crops.

Soybean

Studies on the impact of elevated CO_2 on Soybean (*Glycine max* (L.) Merr.) plants in the water-deficient region of Huang-Huai-Hai Plain, China, showed that elevated CO_2 concentrations improved photosynthesis rate, water use efficiency, and growth Li (2013) under both normal conditions and drought conditions. The CO2Science.org website reports on 108 published experiments between 1985 and 2019 exposing soybean to enriched CO_2 levels. Converted to a +300ppm common scale the average growth benefit was +50.9 percent. There were also ten studies reporting on +600 ppm CO_2 enrichment, which increased photosynthesis by an average of 90.3%.

Maize (corn)

The CO2Science.org website reports on 28 published experiments between 1983 and 2018 exposing corn (*Zea mays* L.) to enriched CO_2 levels. Converted to a +300ppm common scale the average growth benefit was +23.7 percent. Corn also benefits from increased drought tolerance under elevated CO_2. An experimental study (Allen Jr., 2011) exposed plants to water stress conditions in sunlit controlled-environment chambers at 360 ppm (ambient) and 720 ppm (elevated) CO_2. The drought stress caused a 41 percent loss of growth under ambient CO_2 but only a 13 percent loss under elevated CO_2.

Wheat

The CO2Science.org website reports on 92 published experiments between 1983 and 2020 exposing common wheat (*Triticum aestivum* L.) to enriched CO_2 levels. Converted to a +300ppm common scale the average growth benefit was +67.6 percent. Blandino (2020) measured both the yield and nutritional quality of an "improver" hybrid wheat variety and its parents under elevated CO_2 levels (+166 ppm). They reported a grain yield increase of +16 percent but a 7 percent decrease in grain protein levels. But they also found that the food quality of different wheat varietals responded differently to elevated CO_2 levels, so that with proper varietal selection, growers could select wheat types that best take advantage of the elevated CO_2.

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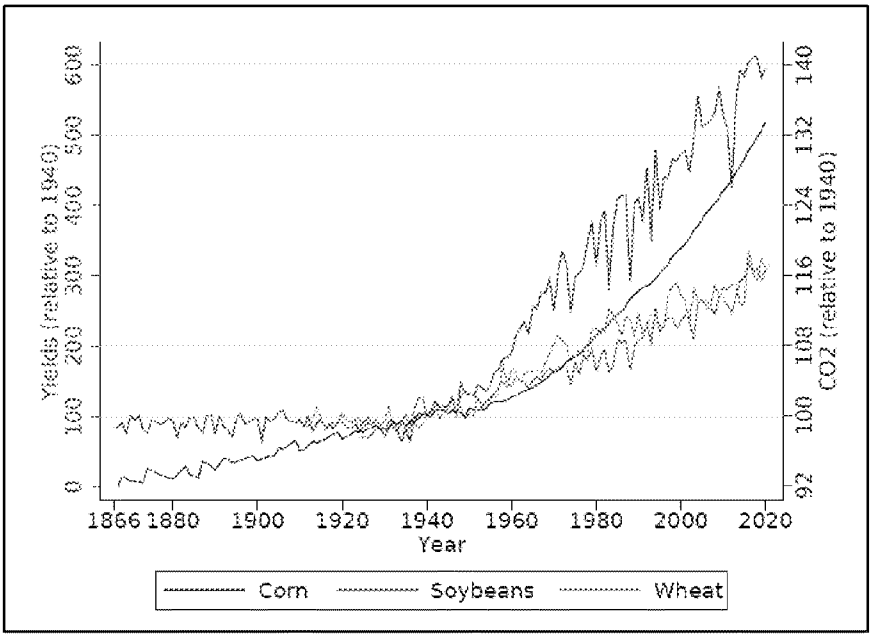

Figure 9.1: U.S. average CO_2 levels and yields of corn, soy and wheat all normalized so 1940=100. Source: Taylor and Schlenker (2021)

Further evidence

A 2021 report from the U.S. National Bureau of Economic Research (Taylor and Schlenker 2021) used satellite-measured observations of outdoor CO_2 levels across the United States, matched to county-level agricultural output data and other economic variables. After controlling for the effects of weather, pollution and technology the authors concluded that CO_2 emissions had boosted U.S. crop production since 1940 by 50 to 80 percent, attributing much larger gains than had previously been estimated using FACE experiments. They found that every ppm of increase in CO_2 concentration boosts corn yields by 0.5 percent, soybeans by 0.6 percent, and wheat by 0.8 percent.

Beyond growth benefits, extra CO_2 boosts plant resilience to dryness. Derying *et al.* (2016) surveyed evidence on crop water productivity (CWP, the yield per unit of water used), drawing attention to the potential for CO_2 both to enhance photosynthesis and reduce leaf-level transpiration (water loss during leaf respiration). They surveyed all available FACE data on crop yield changes for maize (corn), wheat, rice and soybean, and combined it with crop model data simulating yield responses as of 2080 under the extreme RCP8.5 scenario in four growing regions (Tropics, Arid, Temperate and Cold) each of which were split into rainfed and irrigated sub-regions. In every region they reported that models without CO_2 fertilization predicted CWP losses but CO_2 fertilization more than offset them; once fertilization was taken into account, all regions showed a net CWP gain. Deryng et al also reported that negative yield impacts on wheat and soybean were fully offset by CWP gains and mitigated by up to 90 percent for rice and 60 percent for maize. Similarly, Cheng *et al.* (2017) noted that increased global plant growth from 1982 to 2011 due to rising CO_2 uptake was accompanied by such large gains in CWP that despite the extra biomass global water use by plants had not increased.

Deryng *et al.* (2016) assumed that climate change would "exacerbate water scarcity". It is noteworthy that while models predict drylands will expand under climate warming, observations show the opposite: greening is happening even in arid areas. Zhang *et al.* (2024) report that due to increased CO_2 levels "increasing aridity in drylands won't lead to a general loss of vegetation productivity"; increased desertification will happen in at most 4 percent of currently arid areas.

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9.3 Crop modeling meta-analyses

Notwithstanding the abundant evidence for the direct benefits of CO_2 and of CO_2-induced warming on crop growth, in 2023 the U.S. Environmental Protection Agency (EPA 2023) boosted its estimate of the Social Cost of Carbon (SCC) about five-fold based largely on a very pessimistic 2017 estimate of global agricultural damages from climate warming (Moore *et al.*, 2017). One of the two damage models used by the EPA attributed nearly half of the 2030 SCC to projected global agricultural damages based on the Moore *et al.* (2017) analysis. This study was a meta-analysis of crop model studies simulating yield changes for agricultural crops under various climate warming scenarios. Moore *et al.* projected declining global crop yields for all crop types in all regions due to warming.

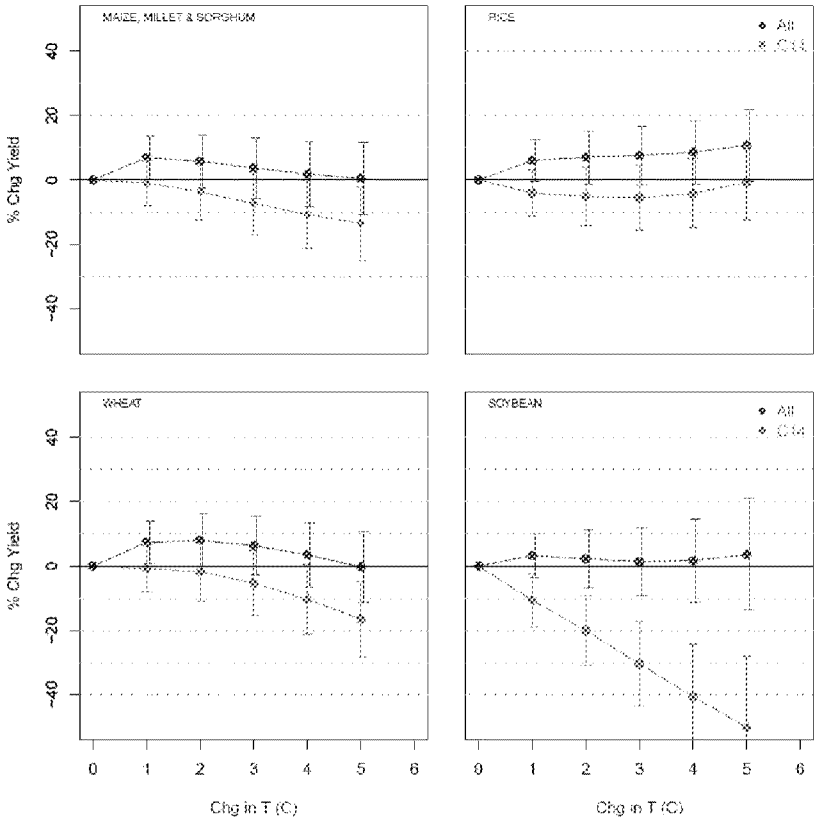

Figure 9.2 Crop yields under CO_2-induced climate warming. Blue: as published in Moore *et al.* (2017). Green: after including omitted data. Source: McKitrick (2025).

McKitrick (2025) re-examined the Moore *et al.* database and found that, while it claimed to cover 1,722 studies, only half the entries (N=862) had complete records, so that the sample available for regression analysis was much smaller than both studies indicated. McKitrick noted that the records most commonly missing were the changes in ambient CO_2 and found that in many cases these could be recovered from the underlying studies or the original climate scenario tables, thereby increasing the usable sample size by 40 percent. The crop yield projections incorporating the newly available data changed considerably. As shown in Figure 9.2, whereas the partial data set implied warming would decrease yield (blue lines), the complete data set implied constant or increase global yields, even out to 5°C warming (green lines).

9.4 CO_2 fertilization and nutrient loss

Evidence has shown that CO_2-induced biomass gains are sometimes accompanied by reductions in the concentrations of protein and other key nutrients such as iron and zinc (Ebi *et al.* 2021). Some experimental evidence has shown that the rising temperatures expected to accompany higher CO_2 levels will offset this loss (Köhler *et al.* 2019) although the evidence for this is mixed, as is the evidence that nutrient dilution observed to date is attributable to higher CO_2 (Ziska 2022). If nutrient dilution does occur under rising CO_2 levels there are several adaptive strategies that could be pursued.

First, selective breeding to raise micronutrient content is already long established (Saltzman et al. 2017) and has proven to be a cost-effective agronomic strategy (Ebi et al. 2021). Strategies can include both conventional breeding and genetically-modified organisms. An example of the latter is Golden Rice, which contains elevated levels of beta-carotene to boost biosynthesis of vitamin A in the human body. Optimal strategies will be location-specific because they vary by crop, climate and soil type (Ebi *et al.* 2021). Second, fortification of food products with micronutrients is already routine. Folic acid (a B vitamin) is added to flour and many other foods; iodine is added to table salt, most commercial breakfast cereals are fortified with iron and numerous vitamins, *etc*. Third, dietary supplements in the form of multivitamin tablets are inexpensive, widely-available and routinely consumed.

One concern about reliance on adaptive strategies is whether they are feasible in low-income countries. Micronutrient deficiency is already a problem in the developing world and dietary supplements have proven to be an effective low-cost response (Ebi *et al.* 2021). It should also be noted the IPCC emission scenarios that generate high levels of warming do so on the basis of high levels of income growth. The SSP scenarios[3] assume that, compared to 2005 levels, global per capita income will double by 2100 in the lowest growth case (SSP3), and in the highest emission case (SSP5) global per-capita income will grow nearly 16-fold. In that scenario even the poorest regions (Africa and the Middle East) end up with a per capita income of about US$126,000, 70 percent higher than current U.S. per capita income (about US$75,000). Consequently the same scenarios in which CO_2 levels increase the most are also those in which global poverty is largely eliminated, in which case all countries would be able to afford dietary supplements as necessary to address micronutrient deficiencies, if they arise and cannot be addressed using on-farm agricultural strategies.

In summary, there is abundant evidence going back decades that rising CO_2 levels benefit plants, including agricultural crops, and that CO_2-induced warming will be a net benefit to U.S. agriculture. To the extent nutrient dilution occurs there are mitigating strategies available that will need to be researched and adapted to local conditions.

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[3] See compilation at Our World in Data.

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10 MANAGING RISKS OF EXTREME WEATHER

Chapter summary

Trends in losses from extreme weather and climate events are dominated by population increases and economic growth. Technological advances such as improved weather forecasting and early warning systems have substantially reduced losses from extreme weather events. Better building codes, flood defenses, and disaster response mechanisms have lowered economic losses relative to GDP. The U.S. economy's expansion has diluted the relative impact of disaster costs, as seen in the comparison of historical and modern GDP percentages. Heat-related mortality risk has dropped substantially due to adaptive measures including the adoption of air conditioning, which relies on the availability of affordable energy. U.S. mortality risks even under extreme warming scenarios are not projected to increase if people are able to undertake adaptive responses.

10.1 Socioeconomic context

Risks from human-caused climate change are affected by natural weather and climate variability and are dominated by the exposure of wealth in coastal and other disaster-prone regions and vulnerabilities of poorer populations. The evolution of climate risk in the U.S. has been dominated by societal factors, rather than by changes to the actual weather and climate hazards. Deaths from weather disasters have decreased substantially since 1900, even as U.S. population grew from 76 million in 1900 to over 331 million in 2020 (Goklany 2011). For example, the Galveston hurricane killed over 8,000 people in 1900 (0.01 percent of the U.S. population), whereas the worst recent disaster, Hurricane Katrina in 2005, killed 1800 people (or 0.0006 percent of the U.S. population) (NOAA National Hurricane Center 2025; U.S. Census Bureau 2025).

Technological advances have substantially reduced losses from extreme weather events. Early warning systems, satellite monitoring, and improved weather forecasting have reduced deaths, although exact numbers are hard to quantify (Deryugina and Hsiang 2023). U.S. weather forecasting has been estimated to reduce losses from weather events with an annualized benefit of $31.5B, protecting lives, property, and supporting agriculture and transportation (NRC 2010). Improved hurricane forecasts have reduced pre- and post-landfall spending, with annual per hurricane cost reductions estimated at $5B (Molina and Rudik 2024).

Infrastructure improvements have contributed to substantial reductions in losses from extreme weather events. Building codes, such as those implemented in Florida after Hurricane Andrew (1992), have reduced losses by ensuring structures can withstand high winds and floods. Homes built after 2002 showed minimal damage during Hurricane Michael (2018), unlike older homes (FEMA 2020). Sea walls, like the Galveston Seawall, protect against wave action and storm surge. The New Orleans Hurricane and Storm Damage Risk Reduction System successfully mitigated storm surge during Hurricane Isaac (2012) (Battelle Memorial Institute 2013). Inland dams in the U.S. help control flooding by storing excess water during heavy rains. It is estimated that the Tennessee Valley Authority (TVA) dams prevent about $309M in annual flood damage in the TVA region and along the Ohio and Mississippi Rivers (TVA, 2025). During Hurricane Helene (2024), TVA's strategies prevented approximately $406M in potential damages (APPA 2024).

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10.2 Data challenges

Since 1980, NOAA has provided a count of annual U.S. weather-related disasters that it estimates to have exceeded $1 Billion (inflation adjusted), showing a substantial increase starting in 2008. NOAA and other government officials have cited the upward trend in the Billion Dollar Disaster series as evidence that climate change is making extreme weather worse (Pielke Jr., 2024). But over time, population and wealth have increased dramatically in the U.S., so when an extreme weather or climate event occurs, there is more damage even if there is no underlying trend in the frequency or intensity of extreme weather. Pielke Jr. (2024) demonstrates that losses per weather disaster as a proportion of GDP have decreased by about 80 percent since 1980, as shown in Figure 10.1. Pielke Jr. (2024) also argued that in addition to relying on opaque data sources and unreported adjustments, NOAA failed to normalize its Billion Dollar Disaster data series properly for changes in population exposure and wealth. In May 2025 NOAA announced it has withdrawn the Billion Dollar Disaster product from publication (Pielke Jr., 2025).

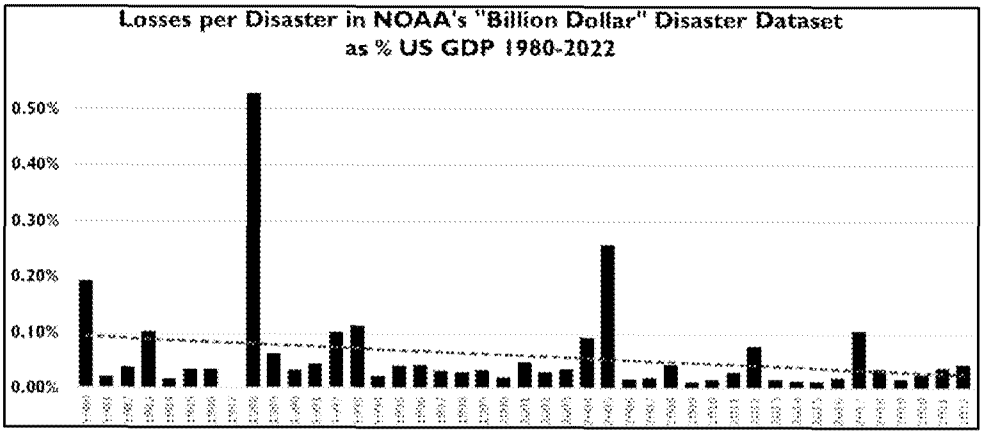

Figure 10.1: Losses per disaster as a % of Gross Domestic Product in NOAA's billion-dollar disaster dataset (the version downloaded in July 2023), 1980 to 2022. Source: (Pielke, Jr. 2024)

In summary, trends in losses from extreme weather and climate events are dominated by population increases and economic growth. Technological advances such as improved weather forecasting and early warning systems have substantially reduced losses from extreme weather events. Better building codes, flood defenses, and disaster response mechanisms have lowered economic losses relative to GDP. Finally, the U.S. economy's expansion has diluted the relative impact of disaster costs, as seen in the comparison of historical and modern GDP percentages.

10.3 Mortality from temperature extremes

10.3.1 Heat and cold risks

Changes in temperature extremes are among the most certain impacts expected in a warming world. It stands to reason that extreme heat events would likely become more frequent while extreme cold events would become less frequent. This pattern is evident in the historical period, though not in the continental U.S. (Chapter 6), and is expected to continue with further warming.

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Mortality during heat extremes is typically caused by heat stroke and heat exhaustion, while mortality during cold extremes typically stems from hypothermia and heart strain. Global mortality is substantially greater for cold conditions than for hot conditions (Zhao et al 2021, Ritchie 2024). Unlike with heat-related mortality, cold-weather risks set in even at moderately cold conditions (Gasparini *et al.* 2015, Lee and Dessler 2023). The U.S. EPA (citing data from the Centers for Disease Control) reports that on average over 1999 to 2015 there were 2.2 deaths per million Americans for which cold was listed as the main underlying cause and an additional 2.4 deaths per million for which cold was listed as a contributing factor (EPA 2025). By contrast there were 1.3 deaths per million for which heat was the main cause and an additional 0.8 per million for which it was a contributor. By this metric cold accounts for approximately double the weather-related deaths as does heat.

Epidemiological methods that consider correlational evidence, not just death certificate reports, indicate the cold/warm ratio might be much higher. A 13-country study of 74 million deaths from 1985 to 2012 estimated that, on average, 7.7 percent of deaths were attributable to sub-optimal temperatures, of which 7.4 percent were attributable to cold and only 0.4 percent were attributable to heat (Gasparini *et al.* 2015). In other words, cold weather killed 18.5 times as many people as did hot weather.

Figure 10.2 shows the distribution of results from Gasparini *et al.* (2015) by country. For the United States the fraction of deaths attributable to temperature was 5.9 percent, of which 5.5 percent was due to cold, thus cold weather killed 14 times as many people as hot weather.

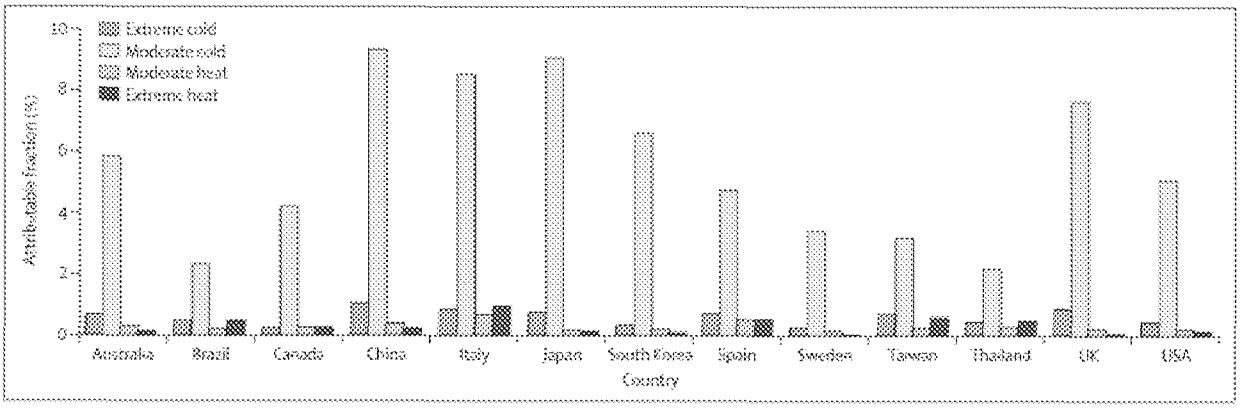

Figure 10.2. Mortality attributable to extreme and moderate cold and heat by country. Source: reproduced from Gasparini *et al.* (2015).

There is strong evidence that people adapt to weather risks. Lee and Dessler (2023) reported that 86 percent of temperature-related deaths across 40 cities in the U.S. were due to cold-related mortality, and that due to adaptation the relative risk of death declined in hot and cold cities alike as seasonal temperatures increased. Allen and Sheridan (2018) found that short, early-season cold events were 2 to 5 times deadlier than hot events, but the mortality risk of both cold and hot extremes drops to nearly zero if the events occur late in the season.

Davis *et al.* (2003) examined heat-related mortality in 28 U.S. cities from the 1960s to the end of the 1990s and found that heat-related mortality declined by three-quarters over the sample period. Bobb *et al.* (2014) examined mortality data for 106 million people in over 100 cities U.S. cities and found a 60 percent decline in average heat-related mortality over the period 1987—2005, from 51 per thousand deaths to 19. They furthermore found that the greatest drop was among seniors over the age of 75. In a study of 42 million

deaths in 211 U.S. cities from 1962 to 2006. Nordio *et al.* (2015) found a more than 90 percent decline in the risk of mortality from excess heat.

In the context of large declines in heat-related mortality, rising temperatures are associated with a net saving of lives since they reduce mortality from cold events. The IPCC AR6 Working Group 2 Chapter 16.2.3.5 (O'Neill *et al.* 2022) acknowledges that heat-related mortality risk is declining over time:

> Heat-attributable mortality fractions have declined over time in most countries owing to general improvements in health care systems, increasing prevalence of residential air conditioning, and behavioral changes. These factors, which determine the susceptibility of the population to heat, have predominated over the influence of temperature change.

Yet the IPCC misrepresents the overall situation in its AR6 Synthesis report. Section A.2.5 of that document states: "In all regions increases in extreme heat events have resulted in human mortality and morbidity (*very high confidence*)." But it is silent on the larger decline of deaths during extreme cold events.

The observed decline in U.S. heat-related mortality has been specifically attributed to adaptation. Wang *et al.* (2018) exploited the spatial variability of heatwave-related mortality across 209 U.S. cities from 1962 to 2006. While simple correlation appeared to imply an increase in mortality risk during heatwaves, accounting for adaptation to heatwave intensity caused the effect to fall to near zero and become statistically insignificant. They used the results of their epidemiological model to project heat-related mortality out to 2050 under four RCP warming scenarios (including RCP8.5) with and without adaptive behavior. Assuming people continue to adapt to the heatwave risks in the regions in which they live. Wang *et al.* (2018) project not only no increase in heat-related mortality, but an overall mortality *decrease* for the U.S. as a whole. They conclude that

> Ignoring adaptation would result in a substantial overestimate of future mortality related to heat waves… Accounting for adaptation, the overall heat-related mortality by 2050 would not change substantially over time compared to 2006.

10.3.2 Mortality risks and energy costs

A 2016 study of U.S. long term mortality risks associated with temperature variations (Barreca *et al.* 2016) showed that increases in mortality across the U.S. are associated with both cold weather and hot weather. But over time, the introduction of electricity and the adoption of central heating and air conditioning (AC) dramatically reduced both risks, especially those associated with hot weather. Prior to 1960, a day above 90°F (32°C) added 2.2 percent to the average mortality risk rate, but after 1960 the same weather added only 0.3 percent to mortality risk, an 85 percent reduction. Prior to 1960 temperatures below 39°F (4°C) added about 1 percent to mortality risk but after 1960 the same weather only added about half that amount. Adaptation through conventional household improvements dramatically reduced public vulnerability to weather extremes. The entire reduction in hot weather mortality was attributable to widespread adoption of indoor AC, which depended on the availability of reliable and affordable electricity.

The corollary of this finding is that the use of heating and cooling systems depends on energy being affordable. Doremus *et al.* (2022) showed that wealthy and poor households in the U.S. adjust their energy expenditures at similar rates in response to moderate temperature swings, but not in response to extreme temperature swings. When temperatures swing to very cold levels (< 5°C) energy spending in high-income

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households rises by 1.2 percent but in low-income households by only 0.5 percent. On very hot days (>30°C) electricity spending in high-income households rises by 0.5 percent but does not change at all in low-income households. The latter result is observed even in subsamples where all households have AC. The implication is that even with widespread adoption of home heating and cooling systems, inability to afford energy leaves low-income households exposed to weather extremes.

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11 CLIMATE CHANGE, THE ECONOMY, AND THE SOCIAL COST OF CARBON

Chapter summary

Economists have long considered climate a relatively unimportant factor in economic growth, a view echoed by the IPCC itself in AR5. Mainstream climate economics has recognized that CO_2-induced warming might have some negative economic effects but they are too small to justify aggressive abatement policy and that trying to "stop" or cap global warming even at levels well above the Paris target would be worse than doing nothing. An influential study in 2012 suggested that global warming would harm growth in poor countries, but the finding has subsequently been found not to be robust. Studies that take full account of modeling uncertainties either find no evidence of a negative effect on global growth from CO_2 emissions or find poor countries as likely to benefit as rich countries.

Social Cost of Carbon (SCC) estimates are highly uncertain due to unknowns in future economic growth, socioeconomic pathways, discount rates, climate damages, and system responses. The SCC is not intrinsically informative as to the economic or societal impacts of climate change. It provides an index connecting large networks of assumptions about the climate and the economy to a dollar value. Some assumptions yield a high SCC and others yield a low or negative SCC (i.e. a social benefit of emissions). The evidence for or against the underlying assumptions needs to be established independently; the resulting SCC adds no additional information about the validity of those assumptions. Consideration of potential tipping points does not justify major revisions to SCC estimates.

11.1 Climate change and economic growth

11.1.1 Overview

It has long been noted that economies tend to do poorly in very cold and very hot regions, with the optimum somewhere in between (Nordhaus, 2006). Temperature-sensitive economic activity migrates, whenever possible, to where it is best suited, and society adapts to the local climate. Based in part on these observations, in 1992 Thomas Schelling, then President of the American Economic Association, argued that any effects of climate change on U.S. economic activity would be small relative to the many other changes that would happen (Schelling 1992).

> … Manufacturing rarely depends on climate, and where temperature and humidity used to make a difference, air conditioning has intervened. When Toyota chooses among Ohio, Alabama, and Southern California for locating an automobile assembly, geographical considerations are important, but not because of climate... Finance is little affected by climate; similarly for health care, or education, or broadcasting. Transportation can be affected, but improvements in all-weather landing and take-off in the last 30 years are greater than any differences that climate makes. If the average effect is a warming, iced waterways and snow removal may decline in importance. Construction is affected, mainly by cold, and if the average effect is in the direction of warming, construction may benefit slightly.
>
> It is really agriculture that is affected. But even if agricultural productivity declined by a third over the next half century, the per capita GNP we might have achieved by 2050 we would achieve only in 2051. …

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> I conclude that in the United States, and probably Japan, Western Europe, and other developed countries, the impact on economic output will be negligible and unlikely to be noticed.

Thirty years later virtually the identical point was made by the IPCC itself in the Fifth Assessment Report (Arent *et al.* 2014, emphasis added)

> **For most economic sectors, the impact of climate change will be small relative to the impacts of other drivers.** Changes in population, age, income, technology, relative prices, lifestyle, regulation, governance, and many other aspects of socioeconomic development will have an impact on the supply and demand of economic goods and services that is large relative to the impact of climate change.

Evidence since AR5 does not change this assessment. Mohaddes *et al.* (2023) found that warm weather shocks have small negative effects on U.S. state-level output but not income, while cold weather shocks negatively affect both and the impacts are about four times larger, implying a shift to warmer conditions would, if anything, yield a net economic benefit for the U.S.

These statements are validated by experience. Since 1900, the average global surface temperature anomaly warmed 1.3°C, about as much as the IPCC predicts will occur in the next century under a moderate emissions scenario. But even as the globe warmed and the population quintupled, humanity prospered as never before. For example, global average lifespan went from thirty-two years to seventy-two years, economic activity per capita grew by a factor of seven, and the death rate from extreme weather events plummeted by a factor of fifty.

While extreme weather events are costly, in all modern economies they are becoming steadily less and less important (Formetta and Feyen, 2019). Since 1990 weather-related disaster losses have declined as a proportion of global GDP (Pielke Jr , 2018, 2020) as have mortality risks (Formetta and Feyen, 2019). While economic weather-related insurance payouts are rising, this is fully explained by the growth in the size of the economy and the value of the insured asset stock. Past increases in episodes extreme weather have not had a significant effect (positive or negative) on the market value of insurance firms (Hu and McKitrick, 2015). Nor have past extreme weather events had a significant effect on U.S. banks' performance (Blickle *et al.*, 2021); warming has even been shown to be beneficial for the finance and insurance sector (Mohaddes *et al.* 2023). Figure 11.1 below is illustrative. For these reasons, economists have long been reluctant to endorse attempts to "stop" climate change or even aggressively reduce GHG emissions because the costs would not be worth it. As one critic of the economics of climate policy put it (Storm 2017):

> Mainstream climate economics takes global warming seriously, but perplexingly concludes that the optimal economic policy is to almost do nothing about it… The contrast is striking. While climate science is sending out loud-and-clear messages that fossil-fuel disinvestment must start now, letting go of coal and oil and diverting resources into renewable energy technology systems, to keep warming below the 2°C limit (IPCC 2014), mainstream climate economics claims that overly ambitious climate targets will unnecessarily hurt the economy and immediate de-carbonization is too expensive. Most climate economists thus recommend humanity to just wait-and-see.

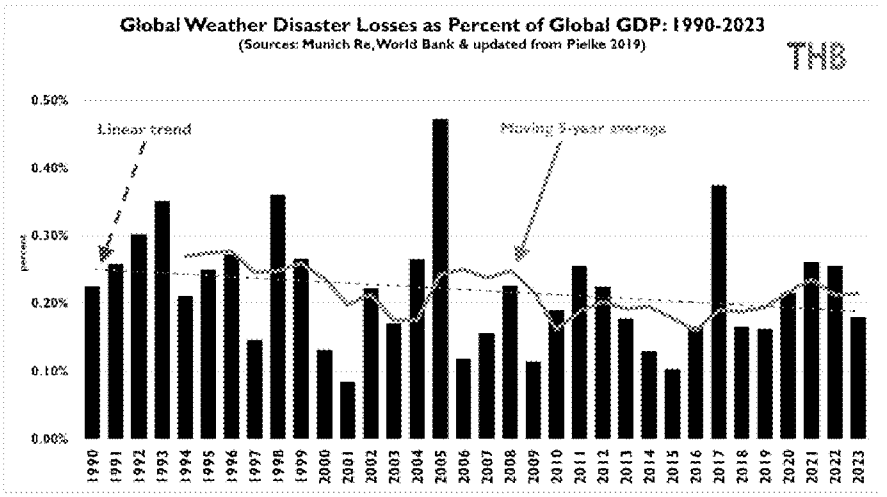

Figure 11.1 Global weather losses as a fraction of GDP. Source: Pielke Jr. (2023)

The mainstream economics position on the climate policy question is best represented by the findings over the past three decades from Integrated Assessment Models (IAMs) of climate change policy, for which Yale economist William Nordhaus was awarded the 2018 Nobel Memorial Prize in economics. IAMs combine economic, climate, and social data into a unified framework for simulating climate damages and evaluating the optimal policy response (Resources for the Future, 2025). Nordhaus' work has generally supported modest global climate policy, with aggressive measures largely deferred to later in the century. Nordhaus developed the so-called Dynamic Integrated Model of the Climate and Economy model, or DICE, in the early 1990s (Nordhaus, 1993) to study the interaction between climate change, climate policy, and global economic growth over long times. DICE assumes global emission control can be coordinated at no cost and asks what the optimal policy target should be. The climate component of the DICE model is based on simplified climatological modeling. The version of DICE at the time of Nordhaus' Nobel Prize award was described in Nordhaus (2018); it had a climate sensitivity parameter of 3.1°C for CO_2 doubling, consistent with the best estimate in IPCC reports (3.0°C).

The baseline (no policy) scenario incurs only $0.4T in global abatement costs and leads to $134.2T (trillion dollars) in global climate damages for a total cost of $134.6T. The climate model component of DICE projects 4.1°C warming by 2100 relative to preindustrial temperatures. Note that this is a higher estimate of warming than many IPCC climate models.

The Optimal Policy scenario barely deviates from the business-as-usual path. It aims for +3.5°C warming, in other words we modestly scale back fossil fuel use and otherwise just live with almost all the warming. This suggests that most CO_2 emissions are less harmful than the policies that would be necessary to abate them. Trying to prevent warming causes costs quickly to outstrip the benefits. Pursuing a goal of capping warming at 2.5°C creates total costs of $177.8T, which is $43.2T worse than doing nothing at all. Nordhaus didn't evaluate trying to reach a Paris-type target of 1.5°C warming but it would be even more costly.

A subsequent edition of DICE includes higher assumed damages from warming which, not surprisingly leads to more aggressive policy recommendations, as explained in the section below on the Social Cost of Carbon.

11.1.2 Empirical analysis of climate change and economic growth

Many other studies have used econometric methods applied to historical data, instead of IAMs, to study the potential impact of climate change on economic growth. Dell *et al.* (2012, herein DJO12) was an influential study that used a multi-country panel of national-level data spanning 1950 to 2005, in which they matched climate and economic data by averaging temperature from the local grid cell level up to the national level using population weights. They found that warming yields an insignificant positive effect on income growth in rich countries but a significant negative effect in poor countries. Moore and Diaz (2015) modified the DICE model to take that finding into account and concluded that it implied a dramatically higher Social Cost of Carbon due to the compounding effects of income loss over time.

A large subsequent literature has debated the robustness of the DJO12 findings. Burke *et al.* (2015) analyzed a global panel with temperatures averaged up to the national level and found a negative effect on growth from warming in rich and poor countries alike when the national average temperature is above 13°C. Zhao *et al.* (2018) used the G-Econ data set of Nordhaus (2006), which breaks economic activity down to the grid cell level, replicated DJO12-type results on the same subset of countries as used in DJO12 but then showed that on the full global sample warming increases growth in rich countries and poor countries alike, though the positive effect in the latter group is confined to where local temperatures are below about 16°C. Greβer *et al.* (2021) developed a regional economic data set for 1,542 sub-national regions around the world between 2005 and 2015 and found temperature had no effect on growth. Yang *et al.* (2023) updated the DJO12 data set and applied an estimator robust to mixed sample frequencies, finding that while temperature shocks exerted a temporary effect on income levels, they did not have a significant lasting effect on growth rates.

Newell *et al.* (2021) noted that there is no underlying theory to guide econometric model specification in this literature. Taking into account the arbitrary choices of which explanatory variables to include they identified over 800 possible model specifications. Using the Burke *et al.* (2015) data they used an estimation method that accounts for model uncertainty and found that the model form preferred by Burke *et al.* (2015), which implied negative effects of warming on growth even in rich countries, is explicitly excluded by the optimal model selection algorithm. Overall they could not detect a temperature effect on GDP or GDP growth, and they estimated the 95 percent confidence interval for the impact on global growth as of 2100 even under the exaggerated RCP8.5 warming scenario spans −86 percent to +388 percent. In other words the net effect is likely positive but too uncertain to distinguish from zero.

Barker (2023) criticized the DJO12 assumption that countries can be grouped into fixed "poor" and "rich" categories based on their incomes many decades ago. He noted that many countries were once poor but became rich over time, and if this is considered the original temperature effects reported by Dell *et al.* became small and insignificant.

Berg *et al.* (2023) argued that countries shouldn't be grouped into large Rich/Poor categories because they are too heterogeneous. They instead estimated country-specific temperature response coefficients then grouped countries with similar response coefficients into small panels. They separately estimated responses to global and idiosyncratic local temperature shocks to better identify the climate signal in weather data. Overall, they found countries experiencing negative effects of warming on growth outnumbered those experiencing positive effects, but only temporarily: eventually the effects reverse such that about twice as many countries experience a net positive growth effect. They also found global (as opposed to local) temperature changes are much more likely to benefit growth in poor countries than rich ones. In a simulation to 2100, even using the extreme RCP8.5 scenario, they computed the average global GDP loss would be only 1.9 percent compared to a scenario with no warming. That is, instead of the economy growing 400 percent it would grow 392%. The implication of Nordhaus' earlier analysis is that trying to prevent the warming would lead to far less than 392 percent growth.

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To summarize, economists consider climate a relatively unimportant factor in economic growth, a view echoed by the IPCC itself in the Fifth Assessment Report. Mainstream climate economics has recognized that CO_2-induced warming might have some negative economic effects but they are too small to justify aggressive abatement policy, and trying to "stop" or cap global warming even at levels well above the Paris target would be worse than doing nothing. An influential study in 2012 suggested that global warming would harm growth in poor countries but the finding has subsequently been found not to be robust (Tol 2024). Studies that take full account of modeling uncertainties either find no evidence of a negative effect on global growth from CO_2 emissions or find poor countries as likely to benefit from it as rich countries.

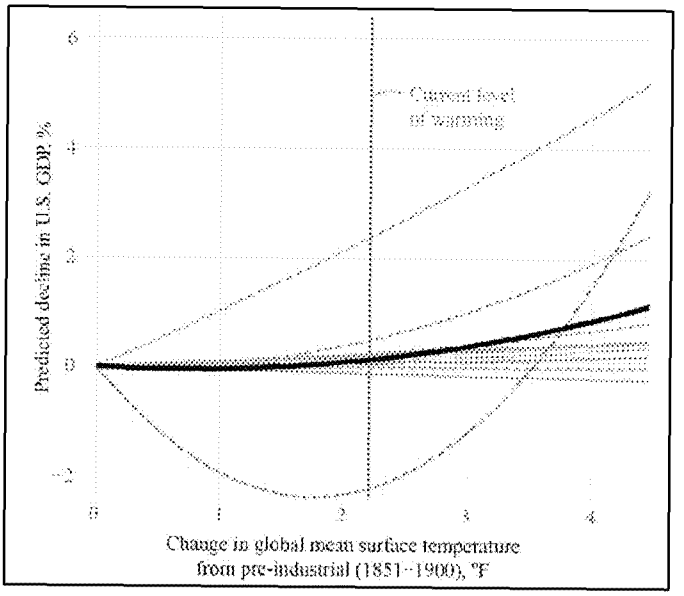

Figure 11.2: Decline in U.S. GDP per degree of warming. Source: CEA-OMB (2023)

The expectation that significant global warming would have a small impact on the U.S. economy was acknowledged quietly by the Biden Administration, even as the President was proclaiming a climate emergency. Figure 11.2, from a 2023 CEA-OMB report, shows the expected decrement in U.S. GDP as a function of temperature rise. The colored lines show the results of a dozen peer-reviewed published studies while the solid black line is their average. The figure could be summarized as "a few percent impact for a few degrees of warming". Given that the economy's annual growth rate is expected to be 1-2 percent, the impact of a warming globe on the U.S. GDP is indeed negligible.

11.2 Models of the Social Cost of Carbon

The Social Cost of Carbon (SCC) is a tool for quantifying the economic impact of carbon dioxide emissions, helping policymakers weigh the costs and benefits of climate policies. It estimates the damage caused by emitting one additional ton of CO_2, expressed in dollars. More formally, the SCC is the discounted present value of the current and future marginal loss of economic welfare due to an additional ton of CO2 entering the atmosphere.

11.2.1 Estimating the SCC

Although the literature refers to "estimates" of the SCC, it is not estimated in the way other economic statistics are estimated. For instance, data on market transactions including prices and quantities can be used to estimate the current inflation rate or the growth rate of per capita real Gross Domestic Product, and there are well-understood uncertainties associated with these quantities. But there are no market data available to measure many, if not most, of the marginal damages or benefits believed to be associated with CO_2 emissions, so these need to be imputed using economic models.

For example, an influential component of some SCC calculations is the perceived social cost associated with a changed risk of future mortality due to extreme weather. There is no market in which people can directly attach a price to that risk. At best economists can try to infer such values by looking at transactions in related markets such as real estate or insurance, but isolating the component of price changes attributable to atmospheric CO_2 levels is very difficult.

Economists use IAMs to compute the SCC. Two of the best known are the Climate Framework for Uncertainty, Negotiation and Distribution ("FUND", Tol 1997) and Nordhaus' DICE. IAMs embed a "damage function" or set of functions relating ambient temperature to local economic conditions. The assumptions embedded in the damage function will largely determine the resulting SCC. IAMs also assume a long-term discount rate or, as in DICE, compute the optimal internal discount rate as part of the solution.

One approach to developing a damage function is to begin with estimates of the costs (or benefits) of warming in specific sectors in countries around the world and aggregate up to a global amount. This was the approach used in FUND. An alternative approach is to develop a simple equation that penalizes global income according to a simple quadratic function of the average global temperature. This approach was used in DICE. In the case of the FUND model many hundreds of parameters had to be selected, whereas in DICE only three were needed and were originally chosen to assign a predetermined penalty (1.2%) to global output as of 3°C warming, with a quadratic term implying that damages grow with the square of the global average temperature anomaly. Barrage and Nordhaus (2024) recently changed the parameters to increase the penalty at 3°C to 1.6%, and added a discrete additional 1.0 percent GDP penalty at 3°C warming to account for "tipping points" (discrete large-scale environmental changes triggered by crossing a warming threshold) and a "judgmental adjustment" of 0.5 percent for excluded impacts at 3°C warming. Not surprisingly the newer version of DICE generates much higher SCC estimates than before.

The concepts of estimation and uncertainty do not readily apply to SCC calculations. By comparison, the question of whether precipitation has trended up or down along the South Carolina coast for the past hundred years can be addressed by collecting rainfall data, estimating a trend parameter and calculating statistical confidence intervals using methods with well-understood mathematical properties. In this way uncertainty can, in principle, be resolved by collecting more data and applying more accurate methods. But no amount of data collection can change the fact that many components of the SCC are unknown and rely on judgment and opinion based on knowledge of the underlying literature on the physical effects of climate change.

SCC calculations are thus best thought of as "if-then" statements: *if* the following assumptions hold, *then* the SCC is $X per tonne. The list of 'if' statements includes the premise that the world's climate and economy work according to the representation in the IAM. One way this might fail to hold is in the timing of warming. Every IAM assumes a value of the Equilibrium Climate Sensitivity (ECS), which controls the amount of warming that results from CO_2 emissions and can be freely varied for the purpose of generating a distribution of SCC values associated with uncertainties over ECS. But as Roe and Baumann (2013) pointed out, time-to-equilibrium increases with the square of ECS, so an upward adjustment of the ECS parameter without an appropriate slowing down of the adjustment process can yield distorted present value damage estimates. In particular, the upper tail of warming associated with some commonly-used ECS distributions is physically impossible for even a thousand years into the future (Roe and Baumann 2013)

yet in an IAM would be realized within a couple of centuries. Failure to align ECS with time-to-equilibrium will lead to an overestimate of the SCC value.

11.2.2 Variations in the SCC

Every level of the IAM calculation includes assumptions, some more influential than others. Key assumptions include the following.

- The discount rate: Climate damages accrue over a long time horizon and costs a century or two in the future need to be discounted to the present. The higher the discount rate the smaller the present value of future damages and vice versa. The discount rate represents the opportunity cost of spending money today rather than investing it and then having more to spend tomorrow. Some economists have argued for the use of very low discount rates in SCC calculations, resulting in policy recommendations that favor relatively large immediate investments in CO_2 emission reductions. The downside is that other investments could potentially earn a larger rate of return for society.
- Equilibrium Climate Sensitivity: IAMs have customarily employed a value of 3.0°C or 3.1°C following the IPCC's guidance. The most recent data-driven ECS values tend to be lower than this (see Chapter 4). Dayaratna *et al.* (2017, 2020, 2023) have shown that use of lower empirically-derived ECS values dramatically lower the resulting SCC estimate, even when low discount rates are used.
- Damage function coefficients: IAMs assume CO_2 and warming cause net harms that increase exponentially with temperature. More recently, IAMs have also incorporated effects from assumed potential climate tipping points. The FUND model took limited but explicit account of CO_2 fertilization effects in agriculture. Since the coefficients were selected prior the publication of the current evidence of global greening and the magnitude of benefits to crops from elevated CO_2 (see Chapters 2 and 9) the growth effects are likely understated. The DICE model (and others) did not explicitly include any CO_2 fertilization benefit, except to the extent it was taken into account in the literature consulted when picking the damage function coefficients. The damage function in FUND contains a region in which low warming yields net benefits in many regions, a finding which is supported by econometric models of warming and growth (Berg *et al.* 2023) and econometric simulations of agricultural changes (McKitrick 2025). The DICE damage function, by construction, rules out net benefits at any warming level.
- Emission scenarios: IAMs generate SCC estimates that increase as the pre-existing concentration of CO_2 increases. Consequently the value of damages later in the century will be higher, depending on the assumed baseline emissions over the coming decades.
- Abatement costs: IAMs represent the cost to the economy of reducing CO_2 emissions. If CO_2 emission reductions are assumed to be inexpensive, then the model will conclude that the optimal policy should aim for deeper emission cuts and vice versa.

It is informative to ascertain whether SCC results are invariant to changes in some assumptions. But when different assumptions result in higher or lower SCC values, the change in the SCC value does not provide *prima facie* evidence about the validity of the assumptions. For example, in 2023 the U.S. Environmental Protection Agency raised its preferred SCC value about 5-fold over the estimates it had issued ten years earlier. This is not because new data had been collected or better mathematical methods had been invented, but because new assumptions had been used, and the validity of those assumptions was a separate question. One was that global agricultural damages were far higher than previously assumed, based on an analysis in Moore *et al.* (2017). But as discussed in Chapter 9, McKitrick (2025) showed that Moore *et al.* (2017) had used a database in which half the CO_2 change observations were missing. When as many of those observations as possible were recovered from underlying sources and the analysis was rerun, the projected crop yield losses disappeared and turned into gains at all warming levels. Hence the portion of the EPA's SCC revision attributable to agricultural yield losses was unwarranted.

11.2.3 Evidence for low SCC

Chapter 2 reviewed evidence on climate change and greening, and Chapter 9 looked at climate change and U.S. agriculture. Evidence shows that CO_2 fertilization has a stronger beneficial effect on agriculture than was known at the time that IAMs like DICE and FUND were parameterized. Haverd *et al.* (2020) found the observed CO_2 fertilization rate has been almost double what had been predicted by crop models. Dayaratna *et al.* (2023) used the updated empirical ECS distribution estimate of Lewis (2022), which assimilates modern instrumental and paleoclimatic temperature records, and allowed for a 30 percent gain in the CO_2 fertilization benefit in the FUND model, and found that, even at a low discount rate of 2.5 percent, the median SCC as of 2050 is only $18.67, with a 24 percent probability of the true value being negative. At a five percent discount rate the median SCC value is negative until the mid-2040s and at 2050 was only $0.37 with a 49 percent probability of being negative. Thus, under reasonable assumptions a mainstream IAM using updated scientific inputs yields evidence consistent with the SCC not being significantly greater than zero.

It should also be noted that the SCC is focused on the social costs of CO_2 emissions from fossil fuel use. It does not measure the private marginal benefits to consumers and society from the availability of fossil fuels. Public willingness to pay for fuels of all types indicates the value to society of reliable, abundant fossil energy. Tol (2017) estimates that the private benefit of carbon is large relative to the social cost. This can be illustrated by noting that the price of a gallon of gas indicates the marginal value to the consumer of the fuel. Suppose we assume a relatively high Social Cost of Carbon of, say, $75 per tonne. Deflated by a MCPF[4] value of 1.5 that would result in a carbon tax of $50 per tonne, which equates to about 44 cents per gallon of gas (Lavelle, 2019). A pre-tax price of $3.00 per gallon would imply the marginal social benefit of the fuel is nearly seven times the marginal social cost.

11.2.4 Tipping points

SCC calculations typically consider gradual impacts of a warming climate, such as slowly-melting glaciers and increasing average temperature. A driver of potentially high values of the Social Cost of Carbon (SCC) is the introduction into models of discrete catastrophic outcomes associated with abrupt changes (Dietz *et al.*, 2021). They are often referred to as "tipping points."

The term "tipping point" mingles two different physical concepts that pose different research challenges. Many physical systems are inherently stable unless acted upon with sufficient external energy. For example, an ice cap might remain intact over a wide range of temperatures but once the temperature crosses the 0°C threshold it melts. Such discontinuities are ubiquitous in nature and require an external force. Whether the force needs to be large relative to the size of the system depends on the underlying stability of the system.

A different type of tipping point is called a *bifurcation* and arises from the study of the internal dynamics of nonlinear systems (Crawford, 1991). Many systems have been observed to have more than one equilibrium point and can move between them with minimal or no external influence. For example, a weather system might have two different equilibrium states: one calm and one with a tornado. A transition from one to another can happen either with no external force or with a minuscule change, such as a flap of the proverbial butterfly's wings (Shen *et al.* 2014). The term "tipping point" is sometimes used to mean a bifurcation of this type and implies instability inherent in the system itself, which is not necessarily dependent on outside forces. It depends, instead, on parameters of the system taking values that support the emergence of bifurcations (Crawford, 1991).

The two different concepts imply different research questions. Regarding the first we are interested in whether components of the climate system are susceptible to abrupt discontinuities in response to

[4] Marginal Cost of Public Funds: the optimal carbon tax rate is the SCC divided by the MCPF (Sandmo 1977).

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sufficiently-large anthropogenic forcing. Regarding the second we are interested in whether the Earth's climate system has inherent bifurcations that imply the possibility of abrupt transitions with or without external forcing.

Models have been developed that imply the second type is a possibility. Kypke *et al.* (2020) presented a simple climate model in which the GHG concentration is one of the parameters that controls the emergence of bifurcations of the Arctic climate to one with both cold and warm equilibria. If sufficiently high GHG forcing combined with a sufficiently high rate of ocean heat transport are imposed a bifurcation becomes possible. More generally GCMs have been observed to contain bifurcations and multiple equilibria (Brunetti and Ragon, 2023).

The possible existence of bifurcations in the Earth's climate system implies abrupt transitions are possible, not just in response to large forcing but also to small perturbations. This places tipping points into the category of low-likelihood and potentially catastrophic events, such as large meteor strikes. A key question to ask is whether those kinds of tipping points can be predicted. Current research has not resolved that question (Dakos *et al.*, 2024) and indeed might not be able to since one implication of the "butterfly effect" is the existence of predictability boundaries of nonlinear systems (Palmer *et al.*, 2014). It is therefore not obvious how to incorporate such possibilities into SCC calculations. Small variations in assumptions will lead to arbitrarily large variations in the resulting SCC with no grounds for choosing among them. If such tipping points are possible the most appropriate stance for economic policy is to maximize resilience to any form of external catastrophe since it is unlikely we could predict it or prevent it from happening.

AR6 (WGI, Chapter 1) focuses mainly on the first type of tipping point, namely an abrupt change in response to external forcing. This is also the meaning associated with popular usage of the "tipping point" concept in discussions of climate change (see https://report-2023.global-tipping-points.org/what-is-a-tipping-point/ for example). As summarized by AR6, there is evidence of abrupt change in the paleoclimate record, and some of these events have been interpreted as tipping points. Some projections with Earth System Models for example have produced tipping points such as Amazon forest dieback in response to specified values of CO_2 concentration or temperature increases.

The alarm surrounding climate tipping points is reflected by *The Global Tipping Points Report* that was launched at the COP28 on 6 December 2023 (Lenton *et al.*, 2023). It identifies more than 25 parts of the climate system said to constitute tipping points. What gets classified as a climate "tipping point" is a moving target. The most common examples in the literature and assessment reports include: Greenland ice sheet disintegration, West Antarctic ice sheet disintegration, summertime disappearance of Arctic sea ice, Amazon rainforest dieback, coral reef dieoff, thawing of permafrost and methane hydrates, Atlantic Meridional Overturning Circulation collapse, boreal forest shift, West African monsoon shift, and Indian Monsoon shift.

All such tipping points require a certain amount of system instability in order to exhibit an abrupt transition in response to warming. For this reason there seems to be very little to discriminate between a tipping event and natural climate variability. Natural climate variability has in the past produced shifts in the West African and Indian monsoons, Amazon forest and coral reef dieback, and disintegration of parts of the Greenland and West Antarctic ice sheets. These impacts can reverse on the decadal and century timescales associated with natural climate variability and ecosystem responses.

Some abrupt changes are potentially more consequential, including collapse of the West Antarctic ice sheet and collapse of the Atlantic Meridional Overturning Circulation (AMOC). AR6 WG1 Summary for Policy Makers states:

> The Atlantic Meridional Overturning Circulation is very likely to weaken over the 21st century for all emission scenarios. While there is *high confidence* in the 21st century decline, there is only *low*

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> *confidence* in the magnitude of the trend. There is *medium confidence* that there will not be an abrupt collapse before 2100. (C.3.4)
>
> There is limited evidence for low-likelihood, high-impact outcomes (resulting from ice-sheet instability processes characterized by deep uncertainty and in some cases involving tipping points) that would strongly increase ice loss from the Antarctic Ice Sheet for centuries under high GHG emissions scenarios (e.g., SSP5-8.5). (B.5.2)

For the purpose of SCC calculations, the research question implied by this type of tipping point is whether such events have been observed in the past in climate conditions similar to what we currently experience or will in the near future. AR6 finds little evidence for impending collapse of the Atlantic Meridional Overturning Circulation or the West Antarctic ice sheet. It finds there is no tipping point associated with Arctic Sea ice (AR6 Technical Summary p. 76)

Dietz *et al.* incorporated several potential tipping points (abrupt changes) into an SCC model and found they added about 25 percent to the estimate, mainly associated with thawing permafrost and release of methane hydrates. However, the IPCC considers this scenario *very unlikely* (AR6 Technical Summary p. 107).

In summary, there might be unknown bifurcation tipping points that are associated with natural climate processes, but this possibility does not translate into specific guidance on the SCC. There are potential abrupt change points in the climate system in response to warming, although the IPCC assigns low probabilities to most, including the largest ones. When these have been considered, the result is only a modest increase in the SCC value in the 21st century.

11.2.5 Are there alternatives?

It is increasingly being argued that the SCC is too variable to be useful for policymakers. Cambridge Econometrics (Thoung, 2017) stated it's "time to kill it" due to uncertainties. The UK and EU no longer use SCC for policy appraisal, opting for "target-consistent" carbon pricing (UK Department for Energy Security and Net Zero 2022, Dunne 2017). However, the uncertainty of SCC estimates doesn't mean that other regulatory measures are inherently better or more efficient. Many emissions regulations (such as electric vehicle mandates, renewable energy mandates, energy efficiency regulations and bans on certain types of home appliances) cost far more per tonne of abatement than any mainstream SCC estimate, which is sufficient to establish that they fail a cost-benefit test.

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12 GLOBAL CLIMATE IMPACTS OF U.S. EMISSIONS POLICIES

Chapter Summary

U.S. policy actions are expected to have undetectably small direct impacts on the global climate and any effects will emerge only with long delays.

12.1 The scale problem

The emissions rates and atmospheric concentrations of criteria air contaminants are closely connected because their lifetimes are short and their concentrations are small; when local emissions are reduced the local pollution concentration drops rapidly, usually within a few days. But the global average CO_2 concentration behaves very differently, since emissions mix globally and the global carbon cycle is vast and slow. Any change in local CO_2 emissions today will have only a very small global effect, and only with a long delay.

Following the emission of a pulse (release) of CO_2 into the atmosphere only about $40\pm$ 15 percent of the extra CO_2 will have been sequestered after twenty years. That fraction rises to $75\pm$ 10 percent after a thousand years, and the remainder will be gradually removed over the ensuing tens of thousands of years (Ciais *et al.*, 2013, pp. 472-473). Consequently, any reduction in U.S. emissions would only modestly slow, but not prevent, the rise of global CO_2 concentration. And even if global emissions were to stop tomorrow, it would take decades or centuries to see a meaningful reduction in the global CO_2 concentration and hence human influences on the climate.

Reducing the atmospheric stock of CO_2 would require emissions to fall below the natural sequestration rate, assuming the entire increase is anthropogenic. Since that rate has been averaging about 50 percent of emissions in recent decades, a reduction of global emissions by 50 percent would (at least temporarily) halt the rise in atmospheric CO_2. The 1997 Kyoto Protocol proposed to cap industrial nations' CO_2 emissions at a modest five percent below 1990 levels by the year 2012. Even though this policy was too difficult for most nations to implement, full compliance would not have substantially reduced atmospheric CO_2 levels. It would only have slightly slowed CO_2 growth, reaching the projected year 2100 level in 2105 instead (Wigley, 1998). Lomborg (2016) estimated that full compliance with the Paris Accord would not stop warming, it would only prevent about 0.1C warming and delay hitting the baseline year 2100 temperature levels by about a decade.

Thus, in contrast with conventional air pollution control, even drastic local actions will have negligible local effects, and only with a long delay. The practice of referring to unilateral U.S. reductions as "combatting climate change" or "taking action on climate" therefore reflects a profound misunderstanding of the scale of the issue.

12.2 Case study: U.S. motor vehicle emissions

The scale problem can be illustrated with reference to U.S. motor vehicles. The EPA's 2009 Endangerment Finding focused on CO_2 emissions from cars and light-duty trucks in the U.S. because Section 202(a) of Clean Air Act mandates the EPA to set emissions standards for motor vehicles if pollutants are found to endanger public health or welfare. The 2009 Endangerment Finding therefore obligated the EPA to regulate emissions from new motor vehicles, ostensibly to reduce or eliminate climate-related harms to the U.S. public.

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Two questions that naturally arise are: (1) How large a reduction in CO_2 emissions would result from such regulation? and (2) What would be the climate impact of such regulation?

The first question can be addressed by comparing U.S. vehicle-based CO_2 emissions to the global total. The second question can be addressed by using the fact that the reduction in global warming would be, according to the models relied upon by the EPA, proportional to the reduction in global emissions, keeping in mind that the change in the CO_2 content of the atmosphere in any given year is the result of total global CO_2 emissions, not just U.S. emissions.

In 2022, the emissions from U.S. cars and light duty trucks totaled 1.05 billion metric tons of carbon dioxide ($GtCO_2$, EPA 2024). Meanwhile global CO_2 emissions from energy use totaled 34.6 $GtCO_2$ (Energy Institute 2024). Hence U.S. cars and light trucks account for only 3.0 percent of global energy-related CO_2 emissions. To a first approximation we can say that even eliminating *all* U.S. vehicle-based emissions would retard the accumulation of CO_2 in the atmosphere by a year or two over a century.

It would also reduce the overall warming trend by at most about 3 percent. For the period 1979-2023, which has the most extensive global coverage of a variety of weather data types, warming trends are determined to a precision of about ± 15 percent, so the impact of reducing the rate of global warming by eliminating U.S. vehicle CO_2 emissions would be far below the limits of measurability. Given that global-average temperature is the most direct climate change metric, impacts on any secondary climate metrics (e.g. severe weather, floods, drought, etc.) from reducing U.S. vehicle CO_2 emissions would be even less measurable.

Consequently, in contrast to the case of local air contaminants like particulates and ozone, even the most aggressive regulatory actions on GHG emissions from U.S. vehicles cannot be expected to remediate alleged climate dangers to the U.S. public on any measurable scale.

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GLOSSARY

2XCO2: Doubling of the atmospheric carbon dioxide (CO2), a commonly used baseline for addressing climate change. In 2025, atmospheric CO2 concentrations were approximately 50 percent of the way to 2XCO2 compared to 1800.

ABATEMENT: In the context of environmental policy, the reduction of emissions.

ACE (Accumulated Cyclone Energy): A statistical measure of a tropical cyclone's energy accumulated over its lifetime, calculated from a summation of the square of maximum sustained wind speeds.

ACIDIFICATION: A commonly used term for the reduction in ocean pH from more alkaline to less alkaline values.

ACRIM (Active Cavity Radiometer Irradiance Monitor) GAP: the gap in total solar irradiance data between 1989 and 1991 caused by a delay in the launch of a satellite-borne monitor in time to overlap and intercalibrate with the prior system.

AEROSOLS: Tiny solid or liquid particles suspended in the air.

ALKALINE: Having a chemical pH greater than 7.0. The "opposite" of acidic, which means a pH less than 7.0.

AMBIENT: Relating to the immediate surroundings of something.

AMO: Atlantic Multidecadal Oscillation, a 60-year cycle of sea surface temperatures in the North Atlantic.

ANTHROPOGENIC: Created by humans.

AR (Assessment Reports): Periodic assessments published by the Intergovernmental Panel on Climate Change evaluating current knowledge of the climate system, global change, and associated issues. An AR now consists of reports from three working groups, the first (WG1) concerned with physical science and the others concerned with societal impacts and mitigation strategies. The most recent was AR6.

ATTRIBUTION: Assertion of a causal relation, chiefly from anthropogenic GHG emissions to observed climate patterns.

AUTOCORRELATION: The phenomenon in which the current value of a random time series variable is correlated with its value in a previous time period.

BIOMASS: The total quantity or weight of organic matter in a given area or volume.

CARBON: The 6th element in the periodic table. Popularly used as a shorthand term for carbon dioxide.

CMIP (Coupled Model Intercomparison Project): The Intergovernmental Panel on Climate Change's organized effort to compare many different global ocean-atmosphere climate models when they are all forced with the same emissions scenario(s). The two most recent were the CMIP5 and CMIP6 for, respectively, AR5 and AR6.

CLIMATE CHANGE: A change in climate due to human influences, as opposed to climate variability which is natural in origin.

CONUS: The contiguous 48 U.S. states.

DICE (Dynamic Integrated model of the Climate and Economy): An Integrated Assessment Model developed by William Nordhaus in 1993.

DISCOUNT RATE: The interest rate used to convert future costs and benefits into their present value. Varies inversely with present value so a high discount rate reduces the present value of future costs and benefits.

DRY ICE: Frozen carbon dioxide.

ECONOMETRICS: The branch of economics concerned with the use of statistical methods (chiefly multiple regression) to analyse economic systems.

ECS (Equilibrium Climate Sensitivity): The total amount of eventual global-average surface warming in response to a hypothetical doubling of the atmospheric CO2 concentration compared to pre-Industrial levels.

EL NIÑO: The warm phase of the El Niño – Southern Oscillation, involving weaker upwelling of cold water off the South American coast and weaker Pacific trade winds.

EMISSIONS SCENARIO: An assumed scenario of future greenhouse gas emissions (or resulting atmospheric concentrations) based upon assumptions regarding global economic activity, the prevalence of fossil fuel use, and (sometimes) global carbon cycle model estimates of the rate of CO2 uptake by land and ocean.

ENDANGERMENT FINDING (EF): The 2009 finding by the Administrator of the Environmental Protection Agency that emissions of well-mixed greenhouse gases (primarily CO2) endanger human health and welfare.

ENSO: El Niño – Southern Oscillation, a prominent natural climate fluctuation involving year-to-year variations in the upwelling of cold water off the equatorial coast of South America and associated strengthening or weakening of trade winds across the Pacific Ocean.

FACE: (Free-Air CO2 Enrichment) Large-scale open-air studies that expose plants to elevated CO2 levels, simulating future climate scenarios.

FOSSIL FUEL: A natural hydrocarbon fuel such as coal, oil, or natural gas formed in the geological past from the remains of living organisms.

FUND (Framework for Uncertainty, Negotiation, and Distribution): An Integrated Assessment Model developed by Richard Tol in 1997.

GBR (Great Barrier Reef): The world's largest coral reef ecosystem located off the northeast coast of Australia.

GDP (Gross Domestic Product): Total market value of all the final goods and services produced within a country's border, usually over one year.

GHCN (Global Historical Climatology Network): A time-varying number of globally distributed weather stations making hourly, daily, or monthly measurements of precipitation, temperature and sometimes snowfall and snow depth.

GLOBAL GREENING: The satellite-observed increase in greenness in most vegetated land areas observed since the early 1980s.

GNP (Gross National Product): Total market value of all the final goods and services produced by the citizens of a country, including exports and imports, usually over one year.

GDP (Gross National Product): Total market value of all the domestically-produced final goods and services produced by the citizens of a country, usually over one year.

GREENHOUSE EFFECT (GHE): The tendency for any planetary atmosphere containing greenhouse gases to be warmer in the lowest layers than if those gases did not exist.

GREENHOUSE GAS (GHG): An atmospheric gas that absorbs and emits infrared radiation, especially water vapor, CO2, and methane.

HURST PHENOMENON: See long term persistence.

HYDROLOGY: The study of the movement of water, especially on land and in the atmosphere.

IAM (Integrated Assessment Model): A computerized tool that combines economics, climate science, and social sciences to provide quantitative relationships between human and Earth systems, helping to inform policy decisions.

IEA (International Energy Agency): A Paris-based intergovernmental organization, established in 1974, that provides policy recommendations, analysis and data on the global energy sector.

IPCC (Intergovernmental Panel on Climate Change): A panel of international experts and governmental representatives established by the United Nations and World Meteorological Organization in 1988 to provide governments at all levels with scientific information that they can use to develop climate policies.

IR (Infrared): Heat radiation that all solid objects and greenhouse gases emit by virtue of their temperature.

LA NIÑA: The cool phase of ENSO, involving stronger upwelling of cold water off the South American coast and stronger Pacific trade winds.

LONG TERM PERSISTENCE (LTP, or HURST PHENOMENON): A form of autocorrelation in which random fluctuations induce long term but not permanent changes in the mean value of a series, which shows up in some climate data series as cyclical or trending patterns on short time scales.

MAIZE: Corn.

MODEL: A computer code or collection of codes which quantify our knowledge of various processes and the interactions between those processes.

MORTALITY: Death or number of deaths, usually expressed for a specific population and period.

NCA (National Climate Assessment): A periodic report mandated by the Global Change Research Act of 1990 summarizing the impact of climate change on the United States. There have been five NCA reports: NCA1 (2000), NCA2 (2009), NCA3 (2014), NCA4 (2017-18), and NCA5 (2023).

OECD (Organization for Economic Cooperation and Development): A group of 38 member countries that have a democratic system of government and free economic systems.

PALEOCLIMATE: Climate of the distant past, before modern weather instruments were widely used (typically pre-1850), necessitating the use of "proxy" measurements such as tree rings, ice core, pollen records, etc.

PDI (Power Dissipation Index): A statistical estimate of the accumulated destructive potential of a tropical cyclone over time, calculated as a summation of the cube of the maximum sustained wind speeds.

PDO: Pacific Decadal Oscillation, a recurring ocean-atmosphere interaction centered over the Pacific basin associated with predominantly warm or cool patterns that influence the global climate.

PHOTOSYNTHESIS: The process by which plants grow, requiring carbon dioxide, water, and light at sufficiently warm temperatures (10 to 35 deg. C for optimal function).

PPM: Parts per million, a measure of the concentration of a substance in (for example) the atmosphere

PRE-INDUSTRIAL: The near-term historical period before which human greenhouse gas emissions were considered significant, usually assumed to be the mid-1700s.

RADIATIVE FEEDBACK: A change in the balance between absorbed solar radiation and emitted infrared (IR) radiation, referenced to the top of the atmosphere, caused by changes in surface temperature.

RADIATIVE FORCING: The change in the balance between absorbed solar radiation and emitted infrared (IR) radiation, referenced to the top of the atmosphere, caused by changes in greenhouse gases, anthropogenic aerosols, volcanoes, etc.

RCP (Representative Concentration Pathway) SCENARIOS: Different scenarios for future greenhouse gas emissions and their impact on the atmosphere, introduced in the IPCC's Fifth Assessment Report (AR5). RCP scenarios have a number label (e.g. RCP6.0) indicating how much radiative forcing they assume in 2100 relative to pre-Industrial times, in Watts per square meter. RCP4.5 and RCP6.0 are intermediate scenarios, whereas RCP8.5 is an extreme scenario with very large future emissions of greenhouse gases.

REGRESSION: A statistical method for selecting the coefficients of a linear equation to explain the behaviour of a dependent variable in terms of variations in one or more explanatory variables.

RICARDIAN ANALYSIS: A method used in environmental economics named after David Ricardo to estimate the economic impacts of climate change, particularly on agriculture, by making use of the hypothesis that expected changes in the return to future agricultural activity will be capitalized into current land values.

SCC (Social Cost of Carbon): An estimate of the net economic damages, measured in present-value dollars, caused by emitting one additional ton of CO2 into the atmosphere.

SSP (Shared Socioeconomic Pathway) SCENARIOS: Different scenarios for future greenhouse gas emissions and their impact on the atmosphere, introduced in the IPCC's Sixth Assessment Report (AR6). Some of the SSP scenarios are analogous to the older RCP scenarios, for purposes of continuity and comparison to earlier climate model assessments.

TC: Tropical cyclone.

TMAX: The daily maximum surface air temperature.

TMIN: The daily minimum surface air temperature.

TOA: Top of atmosphere.

TONNE: Metric ton.

TOXICOLOGY: The study of the adverse effects of chemical substances on living organisms.

TREND: A coefficient, usually estimated using linear regression, representing the slope of a line of best fit through a time series of data, indicating any tendency for the series mean to move up or down over time.

TSI (Total Solar Irradiance): The measure of the total amount of incident solar radiation per unit area, including all wavelengths of electromagnetic radiation, that reaches the Earth's atmosphere. Typically shown in units of watts per square meter (W/m^2).

UHI (Urban Heat Island): The tendency for inhabited areas to be warmer than their rural surroundings, due to the replacement of natural land and vegetation with roads, parking lots, buildings, and waste heat sources.

USHCN: The U.S. Historical Climatology Network, consisting of quality-controlled temperature and precipitation data from 1,218 surface weather stations.

METADATA FOR FIGURES AND TABLES

Figure 2.1 Screen shot from Figure 3 of Zhu *et al.* 2016 https://www.nature.com/articles/nclimate3004

Figure 2.2 Data replotted from Berner 2006 Figure 18, with annotation in red added by authors https://www.sciencedirect.com/science/article/pii/S0016703706002031

Figure 2.3 Screen shot from Gerhart and Ward (2010) Figure 2 https://nph.onlinelibrary.wiley.com/doi/pdf/10.1111/j.1469-8137.2010.03441.x

Figure 2.4 Screenshot from Copernicus Marine Services https://data.marine.copernicus.eu/product/GLOBAL_OMI_HEALTH_carbon_ph_area_averaged/description

Figure 2.5 Screen shot from AIMS (2023) Figures 2-4 https://www.aims.gov.au/sites/default/files/2022-08/AIMS_LTMP_Report_on%20GBR_coral_status_2021_2022_040822F3.pdf

Figure 3.1.1 Screen shot of AR6 WG1 Ch2 Fig 10

Figure 3.1.2 Screen shot of AR6 WG1 Ch7 Fig 7-6

Figure 3.1.3 Author created figure. CO2 data source: https://gml.noaa.gov/ccgg/trends/index.html

Figure 3.2.1 Screen shot from Hausfather *et al.* (2019) Figure S4 https://doi.org/10.1029/2019GL085378

Figure 3.2.2 Author created figure. Data source: Freidlingstein *et al.* (2024) https://essd.copernicus.org/preprints/essd-2024-519
Data source: https://globalcarbonbudget.org/download/1442/

Figure 3.2.3 Author-created using OLS trends, Data source: https://globalcarbonbudget.org/download/1442/

Figure 3.2.4 Author-created using OLS trends, Data source: https://globalcarbonbudget.org/download/1442/

Figure 4.1 Screen shot from Scafetta (2021) Figure 1 https://doi.org/10.3390/cli9110161

Figure 5.1 Data source: https:climexp.knmi.nl/start.cgi. Author-created figure. One ensemble member per model, yearly average temperatures are computed from the global monthly raw temperatures; 'range' is the warmest model temperature minus the coolest model temperature in each year; standard deviation computed across all 33 models' raw temperatures in each year.

Figure 5.2 Screen shot from Scafetta (2023) Figure 2 https://doi.org/10.1007/s00382-022-06493-w

Figure 5.3 Author created figure. Data source: https://climexp.knmi.nl/start.cgi. One SSP370 ensemble member per model. Linear OLS trends computed from global monthly temperature anomalies relative to 1981-2010.

Figure 5.4 Author created figure, based on Figure 3 of McKitrick and Christy (2020)

https://doi.org/10.1029/2020EA001281. Updated using same methods and data extended from 2014 to 2024, see McKitrick and Christy (2025) in chapter references.

Figure 5.6 Screen shot of IPCC AR5 Figure 10.SM1, with author annotations

Figure 5.7 Author created figure following Christy and McNider (2017) https://doi.org/10.1007/s13143-017-0070-z with updated data available at https://www.nsstc.uah.edu/data/cmip6/ERA5_REANALYSES/ and https://www.nsstc.uah.edu/data/cmip6/JRA3Q_REANALYSES/ compiled here https://www.nsstc.uah.edu/data/cmip6/CWG25_Fig_5.7_Table_250627.xlsx

Figure 5.8 Screen shot from https://climate.rutgers.edu/snowcover/chart_seasonal.php?ui_set=nhland&ui_season=1 (accessed May 27, 2025)

Figure 5.9 Screen shot from Rugenstein and Hakuba (2023) Figure 1 https://doi.org/10.1029/2022GL101802

Figure 5.10 Author created figure. Data source https://climexp.knmi.nl/start.cgi. OLS linear trends. One SSP370 ensemble member per model, averaged surface air temperatures for June through August over 31N to 49N latitude, 84W to 102W longitude. Observed temperature data for same months from NOAA/NCEI at https://www.ncei.noaa.gov/access/monitoring/climate-at-a-glance/statewide/time-series for the 12 Corn Belt states averaged together.

Figure 6.1.1 Author replot of Figure 10 from Koutsoyiannis (2013) http://dx.doi.org/10.1080/02626667.2013.804626

Figure 6.2.1 Screen shot of figure from Maue (2025) https://climatlas.com/tropical/

Figure 6.2.2 Author created figure. Data from National Hurricane Center (2024) https://www.nhc.noaa.gov/climo/

Figure 6.2.3 Author created figure. Data from NOAA HRD https://www.aoml.noaa.gov/hrd/hurdat/All_U.S._Hurricanes.html

Table 6.2.1 Author created table. Data from NOAA HRD https://www.aoml.noaa.gov/hrd/hurdat/most_intense.html

Figure 6.3.1 Screen shot from NCA4 Figure 6.4

Figure 6.3.2 Author created figure. Data source: https://www.nsstc.uah.edu/data/ushcn_jrc/

Figure 6.3.3 Author created figure. Data source: https://www.nsstc.uah.edu/data/ushcn_jrc/

Figure 6.3.4 Author created figure. Data source: https://www.nsstc.uah.edu/data/ushcn_jrc/

Figure 6.3.5 Author created figure Data source: https://www.nsstc.uah.edu/data/ushcn_jrc/

Figure 6.3.6 Author created figure. Data source: https://www.nsstc.uah.edu/data/ushcn_jrc/

Figure 6.3.7 Screen shot from https://www.globalchange.gov/indicators/heat-waves

Box tables. Author created table. Data from McKitrick and Christy (2025)

Figure 6.4.1 Author created figure. Data from McKitrick and Christy (2025)

Figure 6.4.2 Author created figure. Data from McKitrick and Christy (2025)

Figure 6.4.3 Author created figure. Data from McKitrick and Christy (2025)

Figure 6.4.4 Author created figure. Data from McKitrick and Christy (2025)

Figure 6.4.5 Author created figure. Data from McKitrick and Christy (2025)

Figure 6.5.1 Author created figure. Data source: https://www.spc.noaa.gov/wcm/data/1950-2024_actual_tornadoes.csv

Figure 6.7.1 Author created figure. Data source: https://www.ncei.noaa.gov/access/monitoring/uspa/wet-dry/0 accessed June 16, 2025. OLS trend line added.

Figure 6.8.1 Screen shot from Lizundia-Loiola *et al.* (2021) Figure 12.

Figure 6.8.2 Screenshot from Marlon *et al.* (2012) Figure 2 panel C. https://www.pnas.org/doi/pdf/10.1073/pnas.1112839109

Figure 6.8.3 Author created Figure. Data 1926 to 2016: https://web.archive.org/web/20200212033452/https://www.nifc.gov/fireInfo/fireInfo_stats_totalFires.html . Post-2017 https://www.nifc.gov/fire-information/statistics/wildfires Accessed June 16, 2025.

Figure 7.1 Screenshot from https://tidesandcurrents.noaa.gov/sltrends/

Table 7.1 Author created table. From Section 6.2 of https://judithcurry.com/wp-content/uploads/2018/11/special-report-sea-level-rise-3.pdf

Figure 7.2 Screenshot from https://tidesandcurrents.noaa.gov/sltrends/sltrends_station.shtml?id=9414290 (downloaded 4/22/25)

Figure 7.3 Screenshot from https://tidesandcurrents.noaa.gov/sltrends/sltrends_station.shtml?id=8771450 (downloaded 4/22/2025)

Figure 7.4 Screenshot from https://tidesandcurrents.noaa.gov/sltrends/sltrends_station.shtml?id=8761724 (downloaded 4/22/25)

Figure 7.5 Screenshot from https://tidesandcurrents.noaa.gov/sltrends/sltrends_station.shtml?id=8518750 (downloaded 4/22/25)

Figure 7.6 Author created figure. Data from https://tidesandcurrents.noaa.gov/sltrends/sltrends_station.shtml?id=8518750

Figure 8.1 Screenshot from https://crudata.uea.ac.uk/cru/data/temperature/HadCRUT5.0Analysis.pdf

Figure 8.2 Screenshot from Hansen and Karecha (2025) Figure 1
https://www.columbia.edu/~jeh1/mailings/2025/CloudFeedback.13May2025.pdf

Table 8.1 Screenshot of column 1 of Table 12.12 IPCC AR6 Working Group I report

Figure 9.1 Screenshot From Taylor and Schlenker (2021) Figure 1
https://www.nber.org/papers/w29320

Figure 9.2 Screenshot from McKitrick (2025) Figure 1
https://www.nature.com/articles/s41598-025-90254-2

Figure 10.1 Screenshot from Pielke (2024) https://www.nature.com/articles/s44304-024-00011-0 Figure 3.

Figure 10.2 Screenshot from Gasparini *et al.* (2015) Figure 2
http://dx.doi.org/10.1016/S0140-6736(14)62114-0

Figure 11.1 Screen shot from Pielke Jr (2023)
https://rogerpielkejr.substack.com/p/global-disaster-losses1990-2023

Figure 11.2 Screenshot from CEA-OMB (2023) https://bidenwhitehouse.archives.gov/wp-content/uploads/2023/03/CEA-OMB-White-Paper.pdf Figure 1.

ABOUT THE AUTHORS

John Christy, Ph.D. is the Distinguished Professor of Atmospheric and Earth Sciences and Alabama's State Climatologist at the University of Alabama in Huntsville. He has a B.A. (Mathematics) from CSU Fresno and an M.S. and Ph.D. (Atmospheric Sciences) from the University of Illinois in Urbana-Champaign. He is a Fellow of the American Meteorological Society and recipient of The NASA Medal for Exceptional Scientific Achievement for constructing, with Dr. Roy Spencer, the first global atmospheric temperature dataset from polar orbiting satellites. He served as Lead Author of the 3rd IPCC Assessment Report (2001), he coauthored the National Academy of Science expert report on Surface Temperature Reconstructions (2006), and he has served on the NOAA Climate Change Science Program, NASA's Earth Science Subcommittee, the National Research Council Space Studies Board and the EPA Science Advisory Board. In addition, Dr. Christy has given testimony in 20 Congressional Hearings.

Judith Curry, Ph.D. is Professor Emerita at the Georgia Institute of Technology, where she served as Chair of Earth and Atmospheric Sciences for 13 years. She is President and co-founder of Climate Forecast Applications Network (CFAN). Curry has a PhD in Geophysical Sciences from the University of Chicago. She has authored or coauthored 192 peer-reviewed papers in atmospheric and climate sciences, two textbooks, and most recently the book *Climate Uncertainty and Risk*. Curry is a Fellow of the American Meteorological Society, the American Association for the Advancement of Science, American Geophysical Union, and a Member of the American Academy of Sciences and Letters. She has served on several Science Steering Committees of the World Climate Research Program and also the DOE Biological & Environmental Research Advisory Committee, Earth Science Subcommittee of the NASA Advisory Council, and the NRC Space Studies Board and Climate Research Committee. Dr. Curry has given testimony in 13 Congressional Hearings..

The Honorable Steven E. Koonin, Ph.D. is the Edward Teller Senior Fellow at Stanford's Hoover Institution. He has served as Under Secretary for Science at the Department of Energy (2009-2011), as Chief Scientist for British Petroleum (2004-2009), and as a professor at Caltech (1975 – 2004, the last nine years as Vice President and Provost). Koonin is a member of the National Academy of Sciences and the JASON group of government advisors, as well as a Governor of Lawrence Livermore National Laboratory, having served in similar capacities for the Los Alamos, Sandia, Brookhaven, and Argonne National Laboratories. Other prior roles include a University Professor at New York University, a non-resident Senior Fellow at the American Enterprise Institute, and a Trustee of the Institute for Defense Analyses. Koonin has a BS in Physics from Caltech and a PhD in Theoretical Physics from Massachusetts Institute of Technology. He authored the 2021 bestseller *Unsettled: What Climate Science Tells Us, What It Doesn't, and Why It Matters*, the 1985 textbook *Computational Physics*, and some 200 peer-reviewed papers in physics and astrophysics, scientific computation, energy technology and policy, and climate science.

Ross McKitrick, Ph.D., is a Professor of Environmental Economics at the University of Guelph in Ontario, Canada. He holds a BA in economics from Queen's University, and an MA and Ph.D. in economics from the University of British Columbia. He has published widely in both economics and physical science journals on topics related to climate change, pollution and public policy. His book *Economic Analysis of Environmental Policy* was published by the University of Toronto Press in 2010. His background in applied statistics has led him to author or coauthor peer-reviewed publications across a wide range of topics in the physical sciences including paleoclimate reconstruction, malaria transmission, surface temperature measurement, climate attribution methodology and climate model evaluation. Professor McKitrick has made many invited academic presentations around the world, was an invited contributor to the 2006

National Academy of Sciences report on Surface Temperature Reconstructions, has served as an expert reviewer for the last three IPCC Assessment Reports (Working Groups I and II) and has testified before the U.S. Congress and committees of the Canadian House of Commons and Senate.

Roy W. Spencer, Ph.D., is a Principal Research Scientist at the University of Alabama in Huntsville. He holds a BS is Atmospheric and Oceanic Science from the University of Michigan, and MS and PhD in Meteorology from the University of Wisconsin -Madison. Spencer's published research has focused on monitoring of weather processes and climate change from Earth-orbiting satellites, as well as using simple physical models for diagnosing climate sensitivity and climate feedbacks. As a NASA Senior Scientist for Climate Studies he served as the U.S. Science Team Leader for the Advanced Microwave Scanning Radiometer (AMSR-E) flying on the Aqua satellite, providing our most accurate global measurements of sea surface temperatures, sea ice, and several other features of the climate system. Along with Dr. John Christy, Spencer developed the first satellite-based technique for global temperature monitoring, for which they received NASA's Exceptional Scientific Achievement Medal and the American Meteorological Society's Special Award.

Pg	Para	Comment or Suggested Edit	
viii	2	The greening effect can't be due to increase in CO2 alone. The fertilization effect needs Nitrogen and phosphorous. There is observational[1] evidence that nitrogen available to plants is decreasing with increasing CO2 and thus acting to limit fertilization effect. Secondly, the greening of some portions of the planet are likely due to changes in precipitation patterns associated with changing climatic conditions and not entirely attributable to fertilization effect. We will also need to consider that the temperature effect on photosynthesis will also be a limiting mechanism to any continued greening dur to fertilization in the future [2]. I recommend acknowledging that the greening is not attributable to CO2 alone and continued greening in the future with increasing CO2 is uncertain. Changed sentence to "Elevated concentrations of CO_2 directly enhance plant growth, globally contributing to "greening" the planet"	[1] Rachel E. Mason et al. Evidence, causes, and consequences of declining nitrogen availability in terrestrial ecosystems. Science376, eabh3767(2022).DOI:10.1126/science.abh3767 [2] C.E. Moore, et lathe effect of increasing temperature on crop photosynthesis: from enzymes to ecosystems. Exp. Bot., 72 (8) (2021), pp. 2822-2844
viii	3	I am glad we acknowledge that CO2 causes warming, though I am not sure why we are not considering other energy sector related emissions that also cause warming (CFCs/HCFCs,methane, aerosol effects). It is not clear what is meant by "CO2 emissions have tended to overestimate observed trends". This is not correct, the cumulative emissions track the RCP8.5 scenario the closest [3,4]. While there was a decrease in emissions during the Covid-19 period the emissions are now back on track following RCP8.5. This statement should clarify what is meant by the statement in the text. Rewrite sentence in the summary section to read "Climate change simulations require scenarios of distant future emissions. There is evidence that scenarios widely-used in the impacts literature have overstated observed and likely future emission trends." On page 16 text added "Schwalm et al. (2020) defended the use of RCP8.5 on the grounds that cumulative CO2 emissions over 2005-2020 track it more closely than the lower RCP scenarios. They also argue that a modified version of the IEA scenarios closely track RCP8.5 in the coming decades. Hausfather and Peters (2020b) responded that the skill of RCP8.5 over those 15 years is due to offsetting errors in its representation of CO2 from fuel use and land use change, and the apparent agreement with IEA in coming decades is due to Schwalm et al. adding in very high land use emissions. The IEA's own projected CO2 emissions track well below RCP8.5."	[3]C.R. Schwalm, S. Glendon,& P.B. Duffy, RCP8.5 tracks cumulative CO2 emissions, Proc. Natl. Acad. Sci. U.S.A. 117 (33) 19656-19657, https://doi.org/10.1073/pnas.2007117117 (2020). [4] C.R. Schwalm, S. Glendon, & P.B. Duffy, Reply to Hausfather and Peters: RCP8.5 is neither problematic nor misleading, Proc. Natl. Acad. Sci. U.S.A. 117 (45) 27793-27794, https://doi.org/10.1073/pnas.2018008117 (2020).

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viii	4	This paragraph seems to be talking about equilibrium climate sensitivity. The most recent model inter-comparison gives a wider range of climate sensitivities in the range of 1.8 to 5.7 and is wider than estimates of climate sensitivities that have been estimated from paleoclimatic and more recent historical datasets, in the range could be in the range of 2.3 to 4.5 K[5]. The higher sensitivity in the most recent model assessments are an area of active investigation by modelers, the feasability of a higher range needs to be confirmed with additional observational and process scale modeling [6]. The range for climate sensitivities, 1.8-2.7, should be corrected to the most recent findings, 2.3-4.5. We should also recognize that the (a)earth is a complex system of systems (b)we can't do an experiment to find out what is correct or reduced the uncertainty. As we get better at extracting temperature records and CO2 concentrations from paelo data, there will be better reconstructions and possibly narrower range along with improvements in modeling that resolve many physical, biological and chemical processes as we get to higher and cloud resolving spatial resolutions. We discuss Sherwood et al. in Ch 4. Sentence changed: "Data-driven methods yield a lower and narrower range."	[5] Sherwood, S. C., Webb, M. J., Annan, J. D., Armour, K. C., Forster, P. M., Hargreaves, J. C., et al. (2020). An assessment of Earth's climate sensitivity using multiple lines of evidence. Reviews of Geophysics, 58, e2019RG000678. https://doi.org/10.1029/2019RG000678 [6] Zelinka, M. D., Myers, T. A., McCoy, D. T., Po-Chedley, S., Caldwell, P. M., Ceppi, P., et al. (2020). Causes of higher climate sensitivity in CMIP6 models. Geophysical Research Letters, 47, e2019GL085782. https://doi.org/10.1029/2019GL085782
viii	5	This is again not true for the majority of the models in the AR6. Figure 7.19 in the IPCC AR6 report shows that majority of the models exhibit a range within the observational range. The models running hot in the most recent decades are the ones with climate sensitivities grate than 5K, which are 3 out of a total of 40 and it should be noted that about the same number of models also are running cold' compared to observed[7] Paragraph has been rewritten: The world's several dozen global climate models offer little guidance on how much the climate responds to elevated CO_2 , with the average surface warming under a doubling of the CO_2 concentration ranging from 1.8°C to 5.7°C [Section 4.2]. Data-driven methods yield a lower and narrower range [Section 4.3]. Global climate models generally run "hot" in their description of the climate of the past few decades– too much warming at the surface and too much amplification of warming in the lower- and mid- troposphere [Sections 5.2-5.4]. The combination of overly sensitive models and implausible extreme scenarios for future emissions yields exaggerated projections of future warming.	[7]Hausfather, Z., Drake, H. F., Abbott, T., & Schmidt, G. A. (2020). Evaluating the performance of past climate model projections. Geophysical Research Letters, 47, e2019GL085378. https://doi.org/10.1029/2019GL085378
viii	5,6, 7	There is very little dispute that these are challenging issues for climate science. Many of the issues identified here related to compound effects (subsidence and se-level rise; wildfire and forest management) that requires further scientific investigation. Identifying further research avenues/focus areas will be helpful to firm up some of the challenges faced in using the climate projections as discussed in the paragraph 9. There is no disagreement here.	

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viii	9	The focus on uncertainty is relevant and should be emphasized in future research. However, as a reasonable policy pathways, making decisions in the face of these uncertainties is critical. Most of the climate uncertainties that we have confidence at this time can be considered Level 2 and Level 3 uncertainties, approaches such as scenario analysis (and others) are suggested and followed for making hazard and risk estimates for future conditions. For deep uncertainty hazards (for example tornadoes etc.) that we don't have enough data or capability to model, developing methods for assessing the uncertainty and risk should be a focus of future research. There is no disagreement here. See Curry's book Climate Uncertainty and Risk.	
2	3	The reason CO2 was identified as a pollutant is the health consequences of increased temperature, flooding and other climate impacts and not because of any direct affect on health dur to exposure to atmospheric CO2[8]. There is no disagreement here.	[8] https://www.cdc.gov/climate-health/php/effects/index.html
3	1/Chapter summary	The summary should note that CO2 fertilization effects are limited by the availability of other critical plant nutrients (Nitrogen, Phosphorous). The fertilization effect is also constrained by higher temperature effecting photosynthesis[9] Added sentence: Other contributing factors included warming and increased nitrogen.	[9] Xinyuan Wei et al 2025 Environ. Res. Lett. 20 064013
3	3	The attribution of greening to primarily CO2 fertilization is questionable as per recent research. Specifically, in the Northern high latitudes (where the greening is most prominent), increases in temperatures due to climate change has been shown to provide the best explanation[10]. In the sub-Saharan region reforestation efforts and changing precipitation patterns lead to some of the observed greening (the great green wall) [11]. The attribution to CO2 fertilization should be qualified by noting the other present and emerging constraints. We cite Zhu et al attributing 70% of change to CO2 . That implies other factors matter as well.	[10]Liu, J., Wennberg, P.O. An emergent constraint on the thermal sensitivity of photosynthesis and greenness in the high latitude northern forests. Sci Rep 14, 6189 (2024). https://doi.org/10.1038/s41598-024-56362-1 [11] Francesco S.R. Pausata, Marco Gaetani, Gabriele Missouri, Alexis Berg, Danielle Maia de Souza, Rowan F. Sage, Peter B. deMenocal, The Greening of the Sahara: Past Changes and Future Implications, One Earth, Volume 2, Issue 3, 2020, Pages 235-250, ISSN 2590-3322, https://doi.org/10.1016/j.oneear.2020.03.002.
3	5	This summarization ignores the compound effects of temperature, moisture and CO2 fertilization in assessing the impacts of CO2 increase on vegetation and crop yields. Many studies have shown that [12]. Making note of these compensating factors is required for a balanced view on CO2 fertilization effects on plants. This issue is addressed in Chapter 9	[12]Lesk, C., Anderson, W., Rigden, A. et al. Compound heat and moisture extreme impacts on global crop yields under climate change. Nat Rev Earth Environ 3, 872–889 (2022). https://doi.org/10.1038/s43017-022-00368-8

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4	1	Chen et al. (2024)[13] conclude that "In the attribution analysis of LAI trend and growth rate trend, there were some differences between multiple linear regression model and partial correlation analysis at high latitudes in the northern hemisphere. Partial correlation analysis showed that LAI trend and growth rate trend in this region were mainly affected by temperature and radiation, while multiple linear regression suggested that CO2 was the dominant driver. The results of the partial correlation analysis seem more reasonable because some previous studies have shown that vegetation change in the high latitudes of the northern Hemisphere is mainly positively affected by climate warming. Multiple linear regression model performed relatively poorly in this region and might not fully identify the contribution of individual drivers. In addition, our model does not include the contribution of land management, which has been highlighted in some previous studies. Of course, the contribution of land management to LAI trend and growth rate trend may be implied in other drivers, such as the positive contribution of CO2 to LAI trend in PP and PN areas". We have added the Chen references. Our existing summary doesn't conflict with this. They conclude CO2 is the dominant driver globally but not the only driver.	[13]Xin Chen, Tiexi Chen, Bin He, Shuci Liu, Shengjie Zhou, Tingting Shi, The global greening continues despite increased drought stress since 2000, Global Ecology and Conservation, Volume 49, 2024, e02791,ISSN 2351-9894,
6	1	This again suffers from not acknowledging the effects of compound and often compensating phenomena that is occurring with the on-going climate change. For example [14] note that much of the Midwest any benefit from CO2 fertilization will be negated by temperature increases. [15] note that "Our results show that long-term physiological acclimation dampens the initial stimulation of plant net carbon assimilation to elevated [CO2], and of plant water use to warming." The topic of agricultural productivity is addressed in Chapter 9 It is not disputed that effects of dT go negative at high enough levels. The 2013 paper by Ruiz-Vera et al doesn't provide much general information beyond the FACE experiment site. The C14 data set I used is a global sample and takes both dT and dC into account.	[14]Ursula M. Ruiz-Vera, Matthew Siebers, Sharon B. Gray, David W. Drag, David M. Rosenthal, Bruce A. Kimball, Donald R. Ort, Carl J. Bernacchi, Global Warming Can Negate the Expected CO2 Stimulation in Photosynthesis and Productivity for Soybean Grown in the Midwestern United States , Plant Physiology, Volume 162, Issue 1, May 2013, Pages 410–423, https://doi.org/10.1104/pp.112.211938 [15] Lamba S, Hall M, Räntfors M, et al. Physiological acclimation dampens initial effects of elevated temperature and atmospheric CO2 concentration in mature boreal Norway spruce. Plant Cell Environ. 2018; 41: 300–313. https://doi.org/10.1111/pce.13079
8	1	The fallacy of these arguments in terms of PH changes and evolution is that the changes described in this paragraph occurred over millennia and the evolutionary process had time to adapt; here with climate change we are talking about changes in our lifetime, the speed of change is the issue. This will lead to collapse of some ecosystem and by the time adaptation takes place it will be millions of years and in a different climate - not the one we have now and that enabled the rise of humans. The chapter notes large regional and even diurnal variations in ocean pH. We already address the issue of short timescale variations on p. 8: "On the time scale of thousands of years, boron isotope proxy measurements show that ocean pH was around 7.4 or 7.5 during the last glaciation (up to about 20,000 years ago) increasing to present-day values as the world warmed during deglaciation (Rae *et al.*, 2018). Thus, ocean biota appear to be resilient to natural long-term changes in ocean pH since marine organisms were exposed to wide ranges in pH."	
5	Fig 2.2	A simple calculation will show us how misleading this figure is. It shows that over 600 Million years CO2 changed by around 6000ppm. That is a rate of change of 0.00001/yr; COE changed from 275 to 430 in the past 175 years, that is rate of change of 0.88ppm/yr. A change in the rate of over 10^5 in magnitude - there in lies the problem. We are seeing a rapid increase in CO2 that has never been witnessed and the ecosystem and huma society (which is at best 10K years old), may not be able to adapt to this rapid change. This figure has been deleted. We don't know what the rate of changes was on an annual or centennial time scale since the data are too low resolution. We have added the following sentence	

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		"While the modern rate of change in CO2 is likely high compared to prior intervals, the geological evidence is that plants and animals evolved under much higher CO2 levels than at present."	
12	Summary	The misuse of RCP8.5 as business as usual is acknowledged. However, this was never intended to be a no-policy or business as usual scenario but as a high-end baseline scenario. When dealing with interaction of physical systems with socio-economic projections (which tend to be highly uncertain and policy dependent), the development of this high baseline scenarios is intended to explore the uncertainty ranges that represent a high-end scenario[16,17]. As any engineer would acknowledge, this is a prudent approach when dealing with L3 and L4 type deep uncertainties and provide valid envelopes for assessing uncertainties and risks from high impact events/hazards. The rest of the statements here are uncertainties acknowledged by the climate scientists and included in developing projections and discussing the results[4]. Does the IPCC downplay the role of sun in climate change? The IPCC includes sun variability in all its assessments from the beginning and has been acknowledged as a potential but insignificant contributor. The comments do not imply any disagreement with what we have written. Extreme scenarios for models are useful for bracketing outcomes but our criticism (based on the literature) is the widespread use of RCP as a no-policy baseline; the reviewer acknowledges that was never its purpose. The IPCC's assessment insignificance of the sun in climate change is based in part on use of low variability irradiance reconstructions that rule out it having any role. This is addressed in Chapter 8	[16]van Vuuren, D.P., Edmonds, J., Kainuma, M. et al. The representative concentration pathways: an overview. Climatic Change 109, 5 (2011). https://doi.org/10.1007/s10584-011-0148-z [17]Hausfather, Z. (2025). An assessment of current policy scenarios over the 21st century and the reduced plausibility of high-emissions pathways. Dialogues on Climate Change, 2(1), 26-32. https://doi.org/10.1177/29768659241304854 (Original work published 2025)
16	2,3,4,5	Please see above. The business-as-usual may be a misnomer but this is an 95% case that is typically included in any type of prudent uncertainty analysis, in particular given the difficulty of predicting the evolution of socio-economic and political conditions over the next 100 years. It should be noted the difference between RCP8.5 and RCP4.5 for mid-century conditions that is of particular focus for adaptation studies in not significant and most of the divergence in these two scenarios occurs later in the century. Implausibility is not equivalent to very unlikely (e.g. 95th percentile), but rather includes impossible or implausible assumptions. High impact hazards occur independent of atmospheric CO2 concentrations (Chapter 6).	

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19	5	That the dynamic vegetation models need more development is acknowledged and is a defining challenge for Earth System Modeling for the next decade. There is no disagreement here	
22	3	As noted, Parker[18,19,20] has investigated the Urban effects on temperature records. The finding establish that by comparing warm and wind conditions world wide that the impact is negligible. However, as noted by authors, this literature hasn't progressed much over the last decade and much more attention needs to be paid to this question by employing newer models, datasets and analytical techniques available to us at present. The CWG Report addresses this concern. We agree with the reviewer that the literature stalled a decade+ ago.	[18] Parker, D. Large-scale warming is not urban. Nature 432, 290 (2004). https://doi.org/10.1038/432290a [19]Parker, D.E. (2010), Urban heat island effects on estimates of observed climate change. WIREs Clim Change, 1: 123-133. https://doi.org/10.1002/wcc.21. [20]Parker, D. E., 2006: A Demonstration That Large-Scale Warming Is Not Urban. J. Climate, 19, 2882–2895, https://doi.org/10.1175/JCLI3730.1.
28	2	We can all agree that there is a desperate need for developing higher-resolution climate models that can get to cloud resolving scale so that we can represent the cloud feedbacks correctly in the model and avoid uncertainties from parameterization and scale dependency of the parameters. This doesn't make these models useless. The models provide directions for further improvements and necessary changes to reduce the uncertainty bands over the ECS. The climate models are useful for research purposes. The CWG Report demonstrates that they are not fit for the purpose of policy making. There's no guarantee increased resolution will be the answer, but if ever a model appears that can deal correctly with clouds that will be quite something. .	

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29	2	The databased approaches have mostly been robust with changes at the high end around 3-4C and at the low end around 1.8 to 2.5C as noted in the chapter. It will be challenging to make this range shorter given the data requirements and uncertainties in data over paleo/haloacene periods. It seems reasonable to estimate that we may have ECS in the range of 3 to 4K (higher than 3.5K being less likely [21]) at the higher end and this should not prevent us from planning and thinking on ways to prevent this possible scenario as it could have major consequences for humans across the planet. The Report acknowledges that 4C is a reasonable upper bound for the likely range	[21] Michael Mann, Our Fragile Moment: How lessons from Earth's past can help us survive climate crisis, Hachette Group Inc., 2024.
32	3	The models range over a factor of three in ECS comparing the most sensitive to the least sensitive models. However vast majority of the models are in 3 to 3.5K sensitivity range and it is probably not correct to assign all models the same amount of importance, given the fact that some of institutes participating in the exercise have different levels of capacity to develop and test models. Only 5 of the models are between 3 and 3.5C. Some of the most reputable models have the highest values of ECS, including UK and US models The point made in this paragraph is that research over several decades has not reduced the range of model ECS. For observers who rely on model outputs this is very concerning and again goes to the question of fitness for purpose, as posed in the prior paragraph.	
34	1	While this analysis for the CMIP6 model set is accurate and focuses on a dataset that has shown higher ECS than previous iterations. it should be noted the models have exhibited considerable skill in predicting the subsequent GMST warming[22]. The criticism of the CMIP6 based high ECS models may be premature and probably will have to wait additional time before passing judgement. As noted in [22] these models have shown considerable skill when evaluated on their projections over the past 30-40 years after the projections were published. Figure 5.3 in the Report clearly refutes this assertion Hausfather et al. did examine early model-obs matches but only using models that had relatively low ECS. The Scaffeta analysis covered a longer interval (1980-2021) than the Hausfather et al. analysis of SAR (1995-2017) and TAR (2001-2017). Its findings line up with Fig 5.3 and the tropospheric evidence in Fig 5.4.	[22]Hausfather, Z., Drake, H. F., Abbott, T., & Schmidt, G. A. (2020). Evaluating the performance of past climate model projections. Geophysical Research Letters, 47, e2019GL085378. https://doi.org/10.1029/2019GL085378
36	1	A recent study attributes the bias to inter-annual availability and residual bias in the satellite record. The pre- and post 2000 have temperature records from two separate satellites and the discrepancy in the trends needs to be resolved[23] Chung et al. (using output through 2014 only) confirm the models' too-high warming rates and suggested two issues that might contribute to at least part of the discrepancy: (1) the differential phasing of natural, ephemeral events such as El Niños between models and observations and (2) a possible spurious cooling in UAH and NOAA/STAR satellite datasets around 2000. Regarding (1) we agree that the timing of major events like ENSOs diminishes the fidelity of models-to-observations comparisons for short periods, but now with 46 years of record as well as two major El Niño warm events since 2014 in the observations, the results shown in Fig. 5.7 are quite appropriate for comparison. Regarding (2) Christy et al. 2018 (and later Zou et al 2023) specifically examined the divergence around 2000 between UAH and NOAA/STAR vs. RSS and UW demonstrating that RSS and UW's use of the aging and drifting NOAA-14 satellite relative to the new, highly calibrated NOAA-15 sensor contributed to a spurious warming in RSS and UW. Be that as it may, CWG Fig. 5.7 is clear in noting all models overestimate the tropical temperature trend relative to observations – model trends being even more positive than those of RSS and the two Reanlayses (in addition to UAH and NOAA/STAR).	[23]Chung, ES., Kim, SJ., Sohn, BJ. et al. Multi-decadal climate variability and satellite biases have amplified model-observation discrepancies in tropical troposphere warming estimates. Commun Earth Environ 5, 342 (2024). https://doi.org/10.1038/s43247-024-01510-8

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38	3	This is challenge we need to face and work on improving the parametrizations. The new era of super high resolution models would resolve the complex interactions of turbulence, transport and clouds and will provide less uncertainty[24]. However, this can't be used to invalidate the entire set of models, the models are performing remarkably well given the complex system that is being modeled. It should be noted the models do cover the range of the observations and it is not outside the envelope of model predictions. The Report does not address invalidating the entire set of models. Rather we address the fitness-for-purpose of the models for policy making Fig 5.6 shows that to the extent there is a match with observations, it comes from models with very little CO2 response. "However, this can't be used to invalidate the entire set of models, the models are performing remarkably well given the complex system that is being modeled." This statement is not supported by the evidence unless and until "remarkably well" is metricized for us to examine and make a determination. The paper cited doesn't exactly apply to the real world (looking at Fig 1 doesn't give one much confidence in models), but does give insight into the various models as best I can tell.	[24]Merlis, T. M., Guendelman, I., Cheng, K.-Y., Harris, L., Chen, Y.-T., Bretherton, C. S., et al. (2024). The vertical structure of tropical temperature change in global storm-resolving model simulations of climate change. Geophysical Research Letters, 51, e2024GL111549. https://doi.org/10.1029/2024GL111549
40	4	Part of the problem here may be which part of the stratosphere is sampled and the importance of interannual a variabilities in the lower part of the stratosphere. [25] have shown that including the stratosphere as defined from 25 to 50km there is high confidence that the cooling signal caused by CO2 increase is detectable and beyond the noise levels of the natural and inter annual variability in the lowest part of the stratosphere. We should put this debate to rest. Santer et al. (2023 has been added to the references with this text: Santer et al. (2023) use updated data to show that a cooling trend has not re-emerged in the lower stratosphere.	[25] B.D. Santer, S. Po-Chedley, L. Zhao, C. Zou, Q. Fu, S. Solomon, D.W.J. Thompson, C. Mears, & K.E. Taylor, Exceptional stratospheric contribution to human fingerprints on atmospheric temperature, Proc. Natl. Acad. Sci. U.S.A. 120 (20) e2300758120, https://doi.org/10.1073/pnas.2300758120 (2023).
42	2	Given the large uncertainties in obtaining data over much of the Northern Hemisphere, using a smaller regional analysis to discount the models may be inappropriate. We should that this remains a question we need to resolve developing better datasets with more seasonal and sub-seasonal coverage to test the model on a global scale The reviewer's points are fine but it is important in the context of this report to point out discrepancies in the way models on some key continental-scale metrics such as, in this case, snow cover. This section directly addresses a region that is important to estimates of the Social Cost of Carbon in the context of agricultural productivity, again reiterating that the models are not fit for the purpose of policy making.	

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44	3	This statement from [26] refers to the fitness of global scale models to resolve regional scale features and argues for developing model at higher spatial resolutions. Using downscaling and other techniques additional insights can be gained at regional scales and provide information for a set of 'purposes'. However, we should work on getting to regional and local scales with GCM as quickly as possible. The current model structural forms may not be adequate for resolving all of these issues merely by increasing spatial resolution. Simulating change at regional to local scales depends on getting the internal variability of the ocean correct, which is only partly a resolution issue.	
47	2	Looking for trends or estimating trends in extreme events in current and future climate is not necessarily an attribution study. Estimating frequency, duration and intensity of events helps understand the changing range of the hazard (if there is one). An attribution would be to find to what extent a particular event is influenced or affected by increase in CO2. I would consider these two not to be the same. We explain the distinction between detection and attribution	
47	3	Attributing any single event to changing climate is perilous, agreed. Yes.	
47	5	As noted by [26] there is not yet any strong evidence that LPT [*sic*] is a fact We have eliminated mention of ~~LPT~~ LTP explicitly, but retain elements of the text surrounding long term variability.	[26]Cohn, T. A., and H. F. Lins (2005), Nature's style: Naturally trendy, Geophysics. Res. Lett., 32; L23402, doi:10.1029/2005GL024476.
57	2	I am not sure how one can conclude that the temperature extremes have decreased based on figure 6.3.4. If I understand correctly the Tmax-Tmin for each year was tabulated and a mean of this difference averaged over the 100+ years was subtracted from these values to get some thing like a anomaly. This anomaly seems to have moved from +3F to -3F over the course of q00 years and now trending upwards again. This suggests to me that there has been significant changes in the extremes over the years and the most recent trend is towards warmer highs? Figure 6.3.3 clearly shows cold extremes have decreased on a centennial scale while warm extremes haven't changed much. In Figure 6.3.4, fFor each station and each year, the hottest day and coldest night are determined and their difference computed. These differences are then geographically averaged for the CONUS and then an overall average is removed to show the results as a type of anomaly. Reviewer 1 is correct, as indicated in the text, Tmin temperatures are almost universally rising more rapidly than Tmax, hence, the difference (or range) has declined overall. A check of CMIP6 models for the CONUS under ssp4.5 shows half with TMax rising faster than TMin and (obviously) half vice versa – so there is no clear signal from models that matches the observations. The flattening (or slight rise in the metric) in the past 20 years is clearly within the natural range, but does reveal an interesting stair-step pattern with rapid declines centered around the 1940's and 1990's and relatively flat periods in between. An explanation is under	

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		investigation, and a leading hypothesis is that there was rapid growth of manufactured surfaces around weather stations in the 1940s. Then, in the 1960s-80s many stations were re-located to relatively rural airports, which then experienced subsequent growth in manufactured surfaces around their weather stations in the 1990s. Thus, rapid nighttime warming in the 1940s and 1990s.	
58	3	The NCA5 is suggesting that the western US is experiencing increase in extreme heat (page 57, para 4); it seems like figure 6.3.5 establishes the fact and not contradict. There was no claim of pervasive (all CONUS) increase in the report We have deleted the sentence "The NCA5 heading "The Risk of Temperature Extremes is Changing" suggests pervasive positive trends are now being observed in threshold temperatures, but that is not evident in the figures above." It isn't ~~Not~~ worth going into more detail in this report	
59	4	The definition of heat wave as consecutive 6 days seems to be a special case. The standard definition is exceedance of 85 or 90 percentile for 2 or more days. I can't check with NCA5 as it was taken down from the web As correctly suggested by Reviewer 1, there are numerous ways to define a heat wave. CWG chose to follow one definition discussed in NCA4 (pg 191) and use 6 consecutive days with Tmax > 90th percentile so as to allow for consistent comparisons. However, changing the parameters will do little to alter the fundamental result that the 1920's to early 1950's contain the major heat wave events for the CONUS.	
60	1,2	Figure 6.3.6 establishes that heatwaves as defined here have increased in the west and have shown increasing trend all over CONUS in the past 50 years. [27] shows the results for the last 60 years and there is little doubt that there is an increase over most of the CONUS, again the NCA5 report is off the web; figure 6.3.7 shows the heat waves are monotonically increasing from the 1960. Including the longer data is only interesting in the dust bowl 1930 camouflage the signal somewhat for the Midwest and central plains. The problem of taking averages over large regions (for example entire CONUS) is that it kills the peak signals and smooths out the emergent climate change indicators. Doing continental averages to look for extremes is really not very useful. Secondly, there is no particular reason to assume that the climate change signal (i.e. the number of heat waves) should showing up 100 years ago, as the CO2 in the atmosphere started to be of significance in the last 50 years. As discussed in the CWG text, the EPA chart is (1) based on nighttime temperatures in the 50 largest US cities and (2) begins in 1961 which was the start of the coolest decade in over 100 years, thereby preconditioning the chart to have an upward trend. Urbanization is most clearly seen in nighttime temperature increases so this does not represent a change in the background climate, but more likely the local climates of cities. Rural areas show less nighttime warming. And, avoiding earlier warm periods does not provide information on the larger scale of natural variability. We have added a sentence at the end of Section 6.3 "Irrespective of the ultimate cause of regional trends, heatwaves have important effects on society which must be addressed, as we discuss in Chapter 10. "	[27]https://www.epa.gov/climate-indicators/climate-change-indicators-heat-waves

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61	4	averaged over all stations in the region, none of these trend parameters is statistically significant'. This is again how one would be looking at statistics of extremes in precipitation. As we know, precipitation is highly heterogenous and location dependent. As observed there are trends even with the approaches chosen by the authors of this study compared to NCA5 and averaging that over and saying there is no trend seems disingenuous. We summarize the site-specific trends as well as the regional average. The rationale for looking at the regional average is that a GHG signal should cover a wide area.	
62	2	same argument as above We summarize the site-specific trends as well as the regional average. The rationale for looking at the regional average is that a GHG signal should cover a wide area.	
63	box	again the issue here is that we are talking about events that are happening in a short-time and over a small region. Averaging over time and space and develop statistics is probably not appropriate when we are talking about events such as the recent flooding event in Texas. If you average that event over 30 days, it will seem unremarkable. Extreme event totals are 1-day to 5-day,s depending on section discussed. The point being made in the Box is that if you use a too-short record you may underestimate natural variability. I'~~m~~ We're not sure how the reviewer's comment challenges this.	
64	1	As noted in NCA5 and shown in the analysis presented in figure 6.4.4 there is a clear trend of increase in extreme precipitation in 12 of the 27 stations analyzed. Again averaging over the entire region is not the best method for picking extreme precipitation events that are local both in time and space. We summarize the site-specific trends as well as the regional average. The rationale for looking at the regional average is that a GHG signal should cover a wide area. Also in this case we point out that the NE behaves differently than other regions.	

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69	2	However, there is evidence that flash droughts, which last weeks have increased over the Northeast and Midwest [28] The paper referenced by Reviewer 1 begins with data so recent (1999) that it cannot provide evidence for long-term changes in drought as evidenced in the US Drought Monitor (DM) even though it suggests an increase in "flash droughts" over that period. Keep in mind, the DM is a product of subjective interpretation and objective measures - objective measures that have changed considerably during the past 25 years – thus is not metrically consistent. (One of the CWG authors was an official contributor to the DM for 15 years.) One would wonder what would the 1920's. 30's and early 50's reveal if the DM was operational back then? A more consistent metric is provided in CWG Fig. 6.7.1.	[28]Ronald D. Leeper, Rocky Bilotta, Bryan Petersen, Crystal J. Stiles, Richard Heim, Brian Fuchs, Olivier P. Prat, Michael Palecki, Steve Ansari
70	2	More recent analysis indicate forest loss due to wildfire accelerating over the recent past[29]. In particular there has been an increase in extreme fire radiative power with a 2 fold increase from 2003 to 2023 (period of satellite data availability)[30][31]. However, that these fires are not out-of-sample and there is a fire deficit as shown in figure 6.8.2 should be acknowledged. But this doesn't alleviate the concern that wildfire is leading to lot of socio-economic concerns and needs to be addressed[32] New sentence added: However there is evidence that the intensity of fires in some regions is worsening (Cunningham et al. 2024) and that wildfires resulted in a net loss of global forest cover over 2001-2019 (Tyukavina et al. 2022).	[29]Tyukavina Alexandra , Potapov Peter , Hansen Matthew C. , Pickens Amy H. , Stehman Stephen V. , Turubanova Svetlana , Parker Diana , Zalles Viviana , Lima André , Kommareddy Indrani , Song Xiao-Peng , Wang Lei , Harris Nancy; Global Trends of Forest Loss Due to Fire From 2001 to 2019, Frontiers in Remote Sensing.Volume 3 – 2022,2022. [30]Cunningham, C.X., Williamson, G.J. & Bowman, D.M.J.S. Increasing frequency and intensity of the most extreme wildfires on Earth. Nat Ecol Evol 8, 1420–1425 (2024). https://doi.org/10.1038/s41559-024-02452-2 [31]Patrick H. Freeborn, W. Matt Jolly, Mark A. Cochrane, Gareth Roberts, Large wildfire driven increases in nighttime fire activity observed across CONUS from 2003–2020, Remote Sensing of Environment, Volume 268, 2022,12777 [32]Parks, S.A., Guiterman, C.H., Margolis, E.Q. et al. A fire deficit persists across diverse North American forests despite recent increases in area burned. Nat Commun 16, 1493 (2025). https://doi.org/10.1038/s41467-025-56333-8
71	3	The question of forest management and its role on wildfire frequency and intensity is interesting and deserves further study. We agree	
80	1	The global mean sea-level was increasing at a rate of 0.08 inches/yr in 1993 compared 0.18 inches/yr in 2023, almost double the rate[33], which is approximately what is needed to meet the NOAA projections by mid-century and seems plausible. ~~We don't judge it to be implausible~~We discuss the NOAA projection for a specific site in the context of high-quality, long-term tide gauge data, but offer no comment on its plausibility. Extrapolating satellite-derived accelerations post 1993 is a perilous business given the well-documented variability of GMSL rates on multi-decadal scales.	[33]Hamlington, B.D., Bellas-Manley, A., Willis, J.K. et al. The rate of global sea level rise doubled during the past three decades. Commun Earth Environ 5, 601 (2024). https://doi.org/10.1038/s43247-024-01761-5

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88	3	A possible reason the method used by IPCC (optimal fingerprinting) can be considered to address McKitnick criticism is in [34] We have added citation Chen et al. They mostly just reiterate ~~my~~ McKitrick's points. They propose a resolution to one part of the problem but it requires very restrictive assumptions.	[34]Chen, H., Chen, S.X. & Mu, M. A statistical review on the optimal fingerprinting approach in climate change studies. Clim Dyn 62, 1439–1446 (2024). https://doi.org/10.1007/s00382-023-06975-5
92	4	The role of clouds remains the single most uncertainty in climate modeling, I am glad this was acknowledged here. Agreed	
93	3	The substance of this paragraph was addressed in my comments in earlier sections. Some of the claims made here are either exaggerations of the usual practice (RCP8.5 being referred to as BAU) or the comment about not fit for purpose (a comment extracted from a publication that is calling out for cloud resolved models. Presumably the reviewer agrees RCP8.5 should not be used as a BAU scenario, so we are in agreement. The Palmer and Stevens paper nonetheless says the models are not currently fit for purpose, an observation echoed by the Nissan et al paper cited..	
105	2,3, 4,5	The problem with both the FACE studies and the soybean. Maize and wheat studies cited here are that they don't consider the effect of increase in temperature, changes in precipitation, humidity and other environmental factors along with CO2 increases. These compound effects have been shown in wide number of studies [35] [36][37][38][39]. A meta analysis of the compound effects shows that increase in CO2, along with temperature, precipitation changes effects the quality of the cereal and yields[40]. Another recent study evaluated the impacts on C3 and C4 crops and conclude that CO2 enrichment for C3 crops could increase but will be compensated by temperature increase. CO2 fertilization effect was found to be small for C4 [41]. It is important therefore that we consider the compound effects on crop yields and not just focus on CO2 enrichment. The reviewer is correct that compound effects need to be considered, and indeed one of the problems with a lot of econometric papers on climate change and agriculture is they only look at heat and ignore the CO2 enrichment (Taylor and Schlenker being an important exception). Since our remit was impacts of CO2 emissions a brief discussion of FACE plot experiments and other CO2-only experiments is on topic. We discuss meta-analysis of multivariate (compound) experiments in Section 9.3.	[35] Ruiz-Vera UM, Siebers M, Gray SB, Drag DW, Rosenthal DM, Kimball BA, Ort DR, Bernacchi CJ. Global warming can negate the expected CO2 stimulation in photosynthesis and productivity for soybean grown in the Midwestern United States. Plant Physiol. 2013 May;162(1):410-23 [36] Levine LH, Richards JT, Wheeler RM. Super-elevated CO2 interferes with stomatal response to ABA and night closure in soybean (Glycine max). J Plant Physiol. 2009 Jun 1;166(9):903-13. [37]Večeřová K, Oravec M, Puranik S, Findurová H, Veselá B, Opoku E, Ofori-Amanfo KK, Klem K, Urban O, Sahu PP. Single and interactive effects of variables associated with climate change on wheat metabolome. Front Plant Sci. 2022 Oct 10;13:1002561. [38]Thomas, J.M.G., Boote, K.J., Allen, L.H., Gallo-Meagher, M. and Davis, J.M. (2003), Elevated Temperature and Carbon Dioxide Effects on Soybean Seed Composition and Transcript Abundance. Crop Sci., 43: 1548-1557. https://doi.org/10.2135/cropsci2003.1548 [39] Lesk, C., Anderson, W., Rigden, A. et al. Compound heat and moisture extreme impacts on global crop yields under climate change. Nat Rev Earth Environ 3, 872–889 (2022). https://doi.org/10.1038/s43017-022-00368-8 [40] Ben Mariem S, Soba D, Zhou B, Loladze I, Morales F, Aranjuelo I. Climate Change, Crop Yields, and Grain Quality of C3 Cereals: A Meta-Analysis of [CO2], Temperature, and Drought Effects. Plants. 2021; 10(6):1052. https://doi.org/10.3390/plants10061052 [41]Rezaei, E.E., Webber, H., Asseng, S. et al. Climate change impacts on crop yields. Nat Rev Earth Environ 4, 831–846 (2023). https://doi.org/10.1038/s43017-023-00491-0

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106	1	Taylor and Schlenker 2021 also note that 'Climate change will likely have negative impact on agriculture in aggregate, especially in regions exposed to extreme heat. And the CO2-driven yield increases may be offset be effects on food nutrition and quality'. However, the results for US have been a net positive in the recent past but not true in the lower latitudes. Extreme heat may be a net negative, but thus far the overall effects have been positive. Regarding nutrition loss see Section 9.4	
111	1,2	The criticism of NOAA Billion dollar map is likely warranted as it was never completely transparent how the data was generated. However, changing the baseline assumption and refactoring the data using a different set of criteria to make the effects smaller also doesn't make sense. We should continue collecting this data and make the data accessible for researchers and peer review. Figure 10.1 doesn't address these issues, it is another methodology with unknown province of the data. We agree that data collection, dissemination and transparency are key. Fig 10.1 is traceable as an indicator though we don't regard it as the final word on the subject either. .	
117	3	Climate change can be expected to increase cold weather extremes in regions that have not been exposed to these effect ~~Not sure what the reviewer's point is.~~ The reviewer's point is unclear.	
118	3	The same Nobel prize winning model in its most recent study concludes that [42] "We conclude with three results relevant for climate policy. First, both current policies (base run) and the extended Paris Accord fall short of limiting global warming to 2 °C or to the cost–benefit optimal level. Second, the economic stakes in global climate policy are substantial, with estimated net present value of economic benefits around $120 trillion from the cost–benefit optimal policy. Third, once differences in discounting are considered, the baseline DICE-2023 estimate of the social cost of carbon ($66/tCO2 for 2020) aligns closely with other recent estimates". Obviously this is the latest and the current version of the model and these results are quite different from thus discussed on this page. These conclusions should also be included in this discussion to avoid selective reading of the literature. We discuss Barrage and Nordhaus (2024) on p. 121.	[42]L. Barrage, & W. Nordhaus, Policies, projections, and the social cost of carbon: Results from the DICE-2023 model, Proc. Natl. Acad. Sci. U.S.A. 121 (13) e2312030121, https://doi.org/10.1073/pnas.2312030121 (2024).

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120	1	Similar empirical studies [43] point to "Using an empirical approach that provides a robust lower bound on the persistence of impacts on economic growth, we find that the world economy is committed to an income reduction of 19% within the next 26 years independent of future emission choices (relative to a baseline without climate impacts, likely range of 11–29% accounting for physical climate and empirical uncertainty). These damages already outweigh the mitigation costs required to limit global warming to 2 °C by sixfold over this near-term time frame and thereafter diverge strongly dependent on emission choices. Committed damages arise predominantly through changes in average temperature, but accounting for further climatic components raises estimates by approximately 50% and leads to stronger regional heterogeneity. Committed losses are projected for all regions except those at very high latitudes, at which reductions in temperature variability bring benefits. The largest losses are committed at lower latitudes in regions with lower cumulative historical emissions and lower present-day income". This study uses more of the daily temperature precipitation from 1600 hundred locations world wide instead of global means. There are numerous studies that show the cost, many described in the COP 21 and follow-on meetings The Kotz et al. paper is subject to a cautionary notice at the Nature website that “the reliability of data and methodology presented in this manuscript is currently in question.” https://www.nature.com/articles/s41586-024-07219-0 The literature showing growth effects of temperature increase is pretty robust. And though we don’t cite it, there is a new paper just accepted at Climate Change Economics by McKitrick and Devina Lakhtakia adding to the evidence using 2 newly-constructed global data bases.	[43] Kotz, M., Levermann, A. & Wenz, L. The economic commitment of climate change. Nature 628, 551–557 (2024). https://doi.org/10.1038/s41586-024-07219-0

Field Code Changed

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Page	para	Comment or Suggested Edit
		The report indicates numerous examples of uncertainties in climate science. It would be extremely helpful if these undertainties were made more explicit, listed in a concluding section, and prioritized in some way - what are the top 10 priority research areas? If the opening remarks by Secretary Wright and the title pointed to uncertainties and the need for more research, I believe this report will be better received. As I read the report and left review comments below, **I bolded items where I gather the authors imply that research is needed**. Consider including these kinds of statements throughout and adding a summary. An interesting suggestion but with the time constraints ~~I suggest~~ this must be deferred to a separate report.
viii	3	This would be more correct: "Some scenarios of future CO2 emissions overestimate observed levels" Sentence has been removed
viii	5	This would be more correct: Some detailed climate models run "hot" in their simulation of the climate of the past few decades, while many have underestimated the amount of surface warming. **More research is needed to select the most skillful and reliable models**. The need for more research on model development is implicit. Again, this would be a good topic for a separate report.
viii	6	Need reference for: "Claims of increased frequency or intensity of hurricanes, tornadoes, floods, and droughts are not supported by historical data." **More research is needed to identify how frequency and intensity of weather events are affected by environmental conditions.** The ES statements are all supported by the document chapters **but ~~suggest we add~~ references will be added to specific sections.**
4ff		It is misleading to separate the photo-chemical effects of CO2 from the temperature effects. Extreme heat is hard on plants, causing them to lose water, close stomata, etc. It depends on the plant and the degree of heat. **More research is needed to understand how the temperature (mean and variability) affects plant productivity and resilience.** 1st paragraph of Section 2.1, we aAdded the sentence "Here we focus just on CO_2 fertilization; research on combined effects due to temperature and precipitation changes are discussed in Chapter 10."
7		Again it is misleading to separate the CO2 and the temperature effects on the oceans. The warming surface waters is having significant impact on ocean fish and habitats due to the overall increase in global temperatures *This section is specifically on changing alkalinity. We haven't included a review of temperature effects on fish populations: it is one of the impacts topics we* were not able to survey.
14	4	More accurate to say "because their effect remain largely unknown". Good examples include natural aerosols (sea salt, dust, biogenic aerosols). Are there others to mention? **More research is needed to understand radiative effects of both natural and anthropogenic sources of radiative variability throughout the atmospheric column.** Sentence added: "Natural sources of global energy imbalance other than volcanoes and total solar irradiance (TSI) are not included in these graphs because their effects remain largely unknown."
17	figure	What scenarios are the models using in this figure? SRES, as stated in text, also others including Hansen A,B,C and others as described in the Hausfather et al. paper.
19		Vegetation is only one way that CO2 is accommodated by land processes, the other is through soils and microbial processes Microbial dynamics is complex and challenging to understand but may also be a way to boost CO2 absorption by soils (which also enriches the soil nutrients!). **More research is needed to better understand how plants and soil systems remove CO2 from the atmosphere.**

		Noted.
19	5	**More research is needed to improve the understanding and representation of land systems, carbon and nutrient fluxes in models.** Noted.
20		Carbon uptake by oceans and ocean ecosystems is less well studies and modeled. The lack of spread of carbon in ocean models may result from insufficient information, ocean biogeochemistry, ecosystems and model development. **More research is needed to study and model carbon, nutrient and ecosystem processes and dynamics in ocean models.** Noted.
		More research is needed to map warming trends in urban, non-urban and other environments and to ensure accurate representation of regional and global trends in temperature. Noted.
27	2	"This practice" - need to clarify whether this refers to "emergent property" or discarding. I believe the authors mean the latter, but it should be made more clear Sentence rewritten: "Parameter tuning to yield an ECS target was commonplace for the models used in AR4; modelers have moved away from this practice with time."
27	3	"assumed positive cloud feedback" - this is an emergent property too, based on simulation/observation. Should be rephrased to not use the word "assumed". **Further research is needed to better understand and model how clouds change with temperature and what the feedback effects are on the radiative balance.** ~~Need to clarify if cloud feedbacks are assumed, imposed or both? Can be handled editorially by deciding whether to delete "assumed" or not; deleting it allows it to remain as an implicit modifier.~~ Sentence has been rephrased without the word "assumed".
		Further research is needed to narrow the uncertainty on climate sensitivity, both using models and observations. Noted.
33		The text and figure refer to 33 models, which would include the best and worst. How much does the uncertainty/range change for a subset of best-performing models? The modeling community doesn't have a leaderboard of best-to-worst models. Some of the "prestige" models from the US and UK have very high sensitivities, but they are preferred by many users for particular applications.
34	figure	How many models are included in each case? High ECS 14, Medium ECS 11, Low ECS 13. Added to Figure caption.
36	figure 5.4	How are the lower and mid-troposphere defined? Standard definitions in the paper: LT surface to ~9km, MT surface to ~15 km. Added in the Fig caption.
37	4	"excess amplification" - amplification of what? And Figure 5.6 shows tropics, is this bias only tropical? Sentence changed: "Another important model-observational discrepancy is the excess amplification or warming with altitude…" The bias is only observed in the tropics but the amplification pattern is only predicted in the tropics. Also bear in mind the tropics is nearly half the atmosphere and is where most solar energy enters the climate system.

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38		**Further research is needed to improve how models represent clouds and dynamics; additional observations are also needed to improve these representations.** Noted.
42		**Further research is needed to improve how models represent planetary albedo to align with observations.** Noted.
		The greater concern with hurricanes is the amount of moisture the carry and drop after landfall, i.e. flooding. While this is an active area of research, it is worth noting that this may be the bigger issue for hurricane change with warming This is covered in the AR6 assessment as quoted, as it's one of the intensity metrics. Currently too little data to assess for trends.
56-57		The concern for many are the extreme hot temperatures without night-time cooling that provides an opportunity for recovery. This section doesn't address this. In this regards, the focus on the difference between extreme hot and extreme cold is misleading when generalizing about decrease in extremes (figure 6.3.4) - the decrease is because we don't have as much extreme cold. This metric is covered by the data in Section 6.3.3.
60		Combining heat and humidity as a measure of extreme heat is not unusual since it is this combination that is most impactful to human health - the body cannot cool if the humidity and heat are both high. Since a warmer atmosphere holds more moisture, and CO2 causes heat (and therefore moisture) to increase, this combination is a relevant assessment of the effects of CO2 on extreme conditions that make it difficult for people. Also combining with urban regions is helpful since that is where most people live. These points are not made in the report and are important. Sentence ~~be~~ will be changed to read: "Given the heatwave definition and urban focus, while these increasing values since 1960 point to a growing human impact they are not informative about long term trends or…" Added a sentence at end of paragraph (Irrespective of the ultimate cause of regional trends, heatwaves have important effects on society which must be addressed, as we discuss in Chapter 10.), which ~~this~~ should address reviewer concerns.
		Patterns and variability of precipitation are poorly understood and models are particularly challenged to represent and predict precipitation, further research in this area is needed Noted.
		The authors rightly describe the extreme uncertainty regarding sea level rise. It would be helpful to add some information about the complex, highly nonlinear and uncertain processes involved with ice-sheet dynamics and ice-sheet - ocean interactions that are especially key for Antarctica. **More research is needed to study and model ice sheet dynamics and ice-sheet ocean interactions.** Noted. Canvassing ice sheet and ocean dynamics in that much detail beyond our scope but would belong in a separate report.
84	3	**Further research is needed on climate variability, effects of ocean circulation, solar variability, model simulation of variability and statistical methods.** Noted.
87-88		Anthropogenic aerosol effects may also influence the inflections in temperature in ways that are challenging to account for Noted.
91	2 and 3	Reductions in erosol indirect (cloud brightening) effects may also explain the reduced planetary albedo, not just from ships but from reduced fossil fuel aerosols coming from the continents, China and east asia especially. This paper describes the reduction in aerosols https://www.nature.com/articles/s41612-023-00488-y **This is another area that needs further research!** Noted.

DOJ_00000689

94	table 8.1	What are the numbers in the 3rd column? Please include in the caption. Good point. Added to caption: "Numbers refer to footnotes in original source that specify locations or region-specific confidence levels."
95	2	I don't see an inconsistency between what Ch 11 and Ch 8 say. The first is about precipitation, droughts, tropical cyclones, heat - overall. The 2nd (ch 8) is about specific types of events in specific regions. Suggest to soften the statement about the contrasting assertions. Sentences at issue are "Evidence of observed changes in extremes and their attribution to human influence (including greenhouse gas and aerosol emissions and land-use changes) has strengthened since AR5, in particular for extreme precipitation, droughts, tropical cyclones and compound extremes" versus "No evidence of emergence in the historical period of a change in river floods, heavy precipitation, drought, fire weather, severe wind storms, and tropical cyclones". ~~It seems apparent to me that~~ Tthese statements are manifestly in conflict.
		The science of attribution of extreme events is challenging and computationally expensive; this is an area where further research is needed with potential to use AI to improve statistics Noted. Not sure about the computationally intensive point: many just run univariate GEV models and overinterpret the results. AI won't fix the bad methodology.
104		This section seems to gloss over many key points. Certainly there are limits where extreme heat and drought (water is key) could be detrimental to crops. It also depends on which crops. There is extensive literature on how certain crop viability is shifting. So a region with particular crop experience and cultivation may no longer be able to sustain that agriculture. There is cost to shifting crops across regions and farmers that needs to be accounted for. And water is key - is there enough water in various regions for energy (power plants need water) as well as agriculture when conditions are very hot for sustained periods? The comment seems to be about the validity of the underlying literature rather than our summary of it. The econometric literature tries to synthesize patterns over large areas to get at overall trends, rather than the agronomy focus on specific sites and crops.
111		Severe weather continues to disproportionately impact lower income communities as well as business that requires outdoor exposure. A thorough analysis would need to include these points and I recommend adding this caveat to the section. This is specifically addressed in Section 10.3.2
		Related to my previous comment, deaths due to extreme heat conditions appear to be increasing, particularly for certain populations and for those with underlying health conditions (which can be hard to detangle when attributing mortality). For example https://jamanetwork.com/journals/jamanetworkopen/fullarticle/2792389 Again this topic is specifically addressed in Section 10.3.2
114		An additional concern is if the grid fails under either extreme heat demands or cold/severe-storm events, the impact on communities will not be uniform and depends on grid infrastructure which can be better in more affluent communities Good point. We don't discuss what makes for grid stability versus instability, especially in the context of many jurisdictions closing reliable power plants and opting for intermittent renewables, but the correlation between extreme weather and the likelihood of power failure is an important topic.
		The impacts of sea level rise and coastal inundation on coastal communities and in low-lying countries should be addressed. This will have impacts particularly on certain countries/regions but also on world economics Good point. The topic is germane but runs into the limits of what we can cover in our limited time. To some extent it is covered in the economics chapter since IAM damage functions include effects of sea level rise on coastal areas.
		Research is needed to better understood the likelihood and impacts of various tipping points, including changes to ocean circulation patterns, ice sheet acceleration, sea-ice loss, die-off of tropical forests, thawing of permafrost, etc. Noted. Hopefully our discussion clarifies the different types of "tipping point" topics.

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		Do the authors think it worthwhile for private or public research, such as at DOE, to seek breakthrough technology that might effectively remove massive amounts of CO2 from the atmosphere? No comment

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Chapter Number	Page Number	Approximate Paragraph Number	Comment or Suggested Edit
	i		In general, criticism and re-analysis of past research is always welcome. This report summarizes some substantial concerns from a small group of researchers. The report should be reframed to reflect this and I provide some suggestions in a later comment. I suspect that simply publishing this report will not offset the hundreds of reports and publications on CO2 and Climate that have come before it. But, new analyses and communication within and outside the research community could make a positive difference, should the findings in this report be substantiated. The DOE Office of Science BER could be provided an opportunity to address the research uncertainties in this document in a thorough and robust manner. Noted.
	iii	1	As someone who used to read the DOE reports on CO2 as a graduate student in the 1990s and then conducted numerous analyses of carbon on many topic areas which were later confirmed by numerous other analyses, it seems somewhat cavalier for DOE to issue one brief conclusive report on the "impacts of carbon dioxide emissions". I suggest the following option: Change the title to "Topics of Uncertainty on the Impacts of Carbon Dioxide Emissions on the U.S. Climate" or "**An Assessment of CO2 Impacts on Climate to Guide Future Research**", and then use this report to drive research/analyses for each report chapter which would conclude in separate topical reports that could be finished within a year or two. In doing so, the DOE would positively contribute to addressing some of these standing issues and hopefully enable the nation to move forward in a more productive manner. Noted. New title: "A Critical Assessment of the Impacts of Carbon Dioxide Emissions on U.S. Climate."
	vii	Forward	I appreciate the perspective. It could be useful to add or edit the Secretary's Forward to indicate that "**the report has been purposefully commissioned to researchers with alternative perspectives in an effort to address these perspectives and provide some closure for the American public, the US Economy, and US energy policy**." I suggest this, because it will be very obvious that a handful of skeptics were chosen out of literally hundreds of extremely active and well-respected scientist. Addressing that upfront will immediately reduce criticism, and hopefully generate a positive environment to address these issues. Everyone would like to see convergence of findings on these issues. Noted. The suggested sentence is not well-phrased, but the reviewer is correct that everyone will see the names and know that the document is coming from a particular perspective. The problem is no such concerns were expressed when people with known biases got put in charge of NCA or IPCC chapters. The path to convergence starts with the wider community admitting that they've been keeping a lid on the necessary discussions. In any event, we do not have any control over the Secretary's Foreword
	viii	2	Any increase in greening from additional CO2 will likely be more than offset by longer growing seasons with higher temperatures (i.e., more days over 100). This causes serious risk to the US midwestern "bread basket", which is why this has been considered a national security concern. The data supporting this trend has been published a few times now in Science by a fellow out of Stanford, among others. Sources: Lobell and Field. 2007, doi: 10.1088/1748-9326/2/1/014002; also Sloat et al. 2020, doi:10.1038/s41467-020-15076-4 has a thorough introduction with many citations. The effects, including compound effects, on Agriculture are addressed in Ch 9

	viii	3	My undertstanding is that the upper bound of emissions (i.e., very high) is business as usual, with no mitigation, and a high-end of growth. It's a worst, yet plausible, case scenario. Similarly, the lowest emissions (i.e., very low) scenario inludes technologies that don't yet exist including significant CO2 removal. Both are there to understand plausible extremes. The more likely scenarios are the low to high scenarios. I'm sure researchers are open to revisiting how things are bounded and presented if there are reasonable objections. It seems that within the expert community people are quick to set RCP8.5 aside as a fringe scenario. The problem is it dominates the impacts literature and the media coverage thereof. So the critical discussion herein is needed.
	viii	4	This may be true. But data driven analyses may not capture anticipated feedbacks. They attempt to by design. Limited by data especially ocean heat content, but they take it into account.
	viii	6	I am a big fan of data and meta-analysis. However, I'll note that I do not think forest management practices are overlooked. In fact, it is one of the main driving story lines (i.e., too much fuelwood exists, so we need to harvest more forest). There remains strong debate on the efficacy of fuelwood removal over large areas as an effective means of wildfire reduction. The key to this analysis is to look at whether the extent (not the numbers) of fires has grown and whether the burned areas are returning to forests or returning to brush or grassland. If it's the latter, then that is more likely due to regional changes in climate (temp and precipitation). Again the issue may be what experts discuss among themselves versus what's out there publicly.
	viii	8	I think we can point to sea-level rise in south florida, crop damage, and disease vectors fairly easily. I'm not aware of what costs are associated with these 3 items, but I suspect it's quite large. Dealt with in Ch 11 on economic costs and the SCC.
	viii	9	Yes, this is an important paragraph. Most scientists are not activists. Just because there is a science finding, scientists don't expect that to turn into policy. The public and the democratic system can determine the policy using an evidence-based risk/benefit analysis, just as noted here. Opening up this conversation (which should have been done decades ago) would be welcome and would better engage the public on this issue. DOE could in fact take a leading role here and help address a major national issue. A point of sincere agreement.
1	2		This is all generally correct. I would like to think this is common knowledge. Yes, but bears repetition
2	4	1	Why use studies based on satellite sensors? I'm quite sure there are studies (again, out of Stanford) that use historic yield data (county-scale USDA data and global FAO data) with associated temperature and precipitation data. Those analyses do not agree with your findings here, I think. But, we can certainly pose these questions to our scientists that study and develop land models and develop a report based on all available data. I'll also note that for sometime data synthesis wasn't considered fundamental science and was therefore largely ignored. Enabling the researchers to conduct robust data analyses on this and other topics would be largely welcomed. See Ch 9 on Ag effects for the studies on yield data.
2	5	Figure 2.2	All data is interesting and useful for perspective and understanding. But isn't the main question whether we are driving up CO2 and temp at a rapid pace in the post-industrial era? This graph does not help answer that question. Figure 2.2 has been deleted.

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2	7	3	Stating that increased aridity in drylands will not lead to decreased productivity seems a bit questionable. We can point to precipitation gradients from high to low precipitation that supports forests to grasslands to shrublands, respecrtively. Less water in general will mean less productivity; this can be seen in different forest compositions as well. The authors cite Zhang et al. (2014), but Zhang's main point is that the direct CO2 effect may be causing greening in drylands that offsets the decreased precipitation. This may be more specific to dryland vegetation, and Zhang et al. specifically state that this finding is relevant to north-east Brazil, Namibia, western Sahel, Horn of Africa, and central Asia. Zhang 2024, not 2014. The point here is to explain benefits of higher CO2 in terms of crop water productivity. Zhang acknowledges increase in desertification (as we note) but points to a global pattern of greening in arid areas.
2	9	3	I do not disagree with this observation of a decline effect, and I have seen it in some of the early biomass energy analyses that appeared in prominent journals and were then corrected over a few years. While it is unfortunate that some try to grab headlines with unsupported assumptions, it does seem that other researchers tend to provide counter arguements and analyses fairly quickly, indicating that the system does in fact work fairly well. Yes, part of the problem is the later counter-evidence gets relatively little attention, hence this report.
3	19	last	Yes, CO2 uptake by land processes have uncertainty associated with them. It's worth noting that DOE researchers (many of whom are retired now) were world-leading and making progress in this area, but nearly all work on CO2 uptake and emissions stopped 10-15 years ago due to political pressure and political concerns. The Carbon Dioxide Information and Analysis Center at ORNL, now cancelled, was a main contributor to the Global Carbon Project. Now the US is woefully behind and ceeding expertise on this to the Europeans (as cited in this report). We are also ceeding expertise on carbon monitoring via satellites to other countries. There's nothing necessarily wrong with this if this is where the US wants to go, but it's important to recognize that we have lost signficant capacity due to policy changes over many years. We specifically recommend the government increase its focus on basic climate monitoring and data dissemination in the “Concluding thoughts” section. The CDIAC was very valuable and we lament its closure.
5	44	1	Some of the early work on this topic was done by researchers at Stanford. But there are plenty of other papers. Here's one that came up in a quick search: https://www.pnas.org/doi/10.1073/pnas.0906865106 We discuss this paper in Ch 9.
5	44	1	Contradicting a number of large meta-analyses on the topic of decreased yields with increased temperature is ok. That's what science is all about. But it's going to have to be done in a more robust way than a couple paragraphs here with one or two citations. This section concerns temperature trends in the corn belt; the discussion of yields is in Ch 9.
6	47	chapter summary	This is very important. I have not dug into the data on extreme storm data (both numbers and intensity). Getting researchers together that disagree on a topic, analyze the data, and publish findings together can be very productive. DOE could sponsor a workshop and bring together a broad range of experts and find answers to extreme weather trends. Good idea

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6	47	chapter summary	I conducted some analyses on wildfire years ago. I saw the bias in the university textbooks and in the wildfire working groups, who essentially went by textbook teachings. It was rare that people went back to the original data. The last time I checked the actual data (a good 10 years ago), I found that…you're correct...the number of fires had not changed much. What does seem to be changing is that the extent of fires has grown, and this is mostly attributable to hotter and drier conditions. I do not believe there is more fuel load now than there was before the US was settled. Arguing that harvesting will decrease fire is nonsensical; you have no idea where the lightning is going to strike and subsidizing the thinning of all forest in the western fire zone would be cost prohibitive. I think we need to stop using wildfire management as a justification for harvesting. If we want to harvest more, than do it, and stop using fuel load arguments (which is more of a concept than proven reality) as a reason to do it. The biggest issue here is encroachment of housing communities into the Wild-Urban Interface (WUI) and how we want to handle that with policies. Fire is really only bad if it's burning someone's house down. Otherwise, it's a natural progression in forest dynamics. Sources: Campbell et al. 2012. doi:10.1890/110057.; Schoennagel and Nelson. 2011. doi:10.1890/090199. Excellent comments. It's a big topic we can only glance at but we are trying just to get some pertinent data into the discussion.
6	57	6.3.2	The NCA5 is cited here and elsewhere. However, the USGCRP website that hosts the NCA reports has been removed. Hence, there is no way to read and review the referenced findings. This DOE report is therefore arguing against something that no longer exists, and that may appear questionable. Noted. Out of our control.
7	74	2	Given the satellite observed ice sheet dynamics, I'm not sure that ice sheet retreat is that hypothetical. Our reference is to hypothetical instabilities, i.e. massive disintegration.
7	all		This is the first time I have seen all sea-level rise estimates discredited by an offset from land subsidence. This is certainly a global dynamic that we would want to capture and understand in Earth system models, and DOE can look into this further with analyses and experiments if necessary. Noted.
8	86	all	This and other chapters cite the IPCC AR6. The IPCC provides a global process to address the issues and uncertainties in this report. Perhaps this report can set a path for pivoting research and re-engaging in a useful manner. That's a big ask.
9	104	chapter summary	The last sentence in this summary is not necessarily accurate. The authors cite Ainsworth and Long (2020) with respect to increased CO2 effects on crops. But, Ainsworth and Long (2020) indicate that increased temp and decreased precipitation will have negative impacts on crops, while increased CO2 may offset some of those negative effects. It is the impact of CO2 on climate and the subsequent impact on crops that is the concern; not the direct effect of CO2 on crops. Rewritten: "There is reason to conclude that on balance climate change has been and will continue to be neutral or beneficial for most U.S. agriculture.

DOJ_00000695

Chapter Number	Page Number	Approximate Paragraph Number	Comment or Suggested Edit
2	3	2.1.1, para. 2	Zheng not in reference list. Do you mean Zeng? Yes, fixed.
2	3	2.1.1, para. 3	"nearly double"? Why exaggerate? - it's a 76% increase. And they reported that future increase in GPP in extra-tropical northern hemisphere (e.g., U.S.) for [CO2] from 300 to 600 ppm of 42%, or 32% more than previous predictions (not 76%). Replace "nearly double" with "much larger than"
2	3	2.1.1, para.1	Zhu also explained that "other factors (OF) not considered in models, such as forest management, grazing, changes in cultivation practices and varieties, irrigation and disturbances such as storms and insect attacks, can be a cause of mismatch between observed and simulated LAI trends…. OF contributes the most to the observed LAI trend over 25.0% (increase) and 5.3% (decrease) of the vegetated area" We don't claim CO2 is the only factor.
2	3	2.1.1, para.2	This report is meant to focus on the U.S., so it would be more appropriate to discuss greening trends in the U.S. Fig. 2.1 shows that the trend in LAI across much of the U.S., with the exception of the Southeast, is less than the global average. Negative OF effects are mainly found in northern high latitudes (e.g., Alaska). Growing season warmth is the dominant factor in cold regions (10.1038/s41558-018-0258-y). Significant browning also is occurring in parts of Alaska (10.1175/EI-D-20-0025.1) But the effect is still positive. In Ch 9 we discuss US-specific evidence concerning CO2 and crop yields.
2	3	2.1.1, para.2	Greening of the Arctic can have important adverse consequences. Direct observations support that warming and increased vegetation cover in the Boreal-Arctic region showed a "robust increasing trend of CH4 emissions (+8.9%) with strong inter-annual variability. The majority of emission increases occurred in early summer (June and July) and were mainly driven by warming (52.3%) and ecosystem productivity (40.7%)." Yuan et al 2024 (10.1038/s41558-024-01933-3). We don't claim it's good or bad, only that it's been observed.
2	3	2.1.1, para.3	Wang et al 2020 (10.1126/science.abb7772) report a decline over recent decades in CO2 effects on global photosynthesis, possibly due to increasing nutrient interactions or interactions with effects on LAI. It's a controversial finding that attracted skeptical comments in *Science* regarding the validity of the satellite data and the statistical methods used https://www.science.org/doi/10.1126/science.abg2947 https://www.science.org/doi/10.1126/science.abg4420 https://www.science.org/doi/10.1126/science.abg5673 While the authors in reply defend the satellite data, they acknowledge they may not have dealt adequately with confounding non-CO2 factors. So, it seems premature to invoke this result.

2	4	2.1.2	Much of this information in this section is appropriately covered in chapter 9 on agriculture. Chapter 2 purports to have a wider focus (global and environment responses), so it should not dwell on responses of individual crop plants (crops account for only 15% of global GPP). There has been plenty written on ecosystem response to eCO2, but evidence such as Fig. 2.3 is not relevant. All analyses of direct eCO2 effects reveal an overriding interaction with other environmental factors (nitrogen and temperature), and global models show that eCO2 only partially compensates for the negative effects of climate change on ecosysem carbon response. We struggled with how to divide material up in Ch 2 and Ch 9. Our solution was that here we are addressing direct CO2 effects, namely CO2 fertilization; later we discuss Ag effects in more detail. Not everyone paid attention in high school biology. Figure 2.3 serves as an illustration of a point that non-specialists are often surprised to learn, namely that CO2 is plant food.
2	4	2.1.1, last para.	Zhang, 2025 (10.1016/j.ecolind.2025.113762) reported that although vegetation cover was increasing, resilience against external disturbances (drought, heatwaves, wildfires) has simultaneously declined. They use the lag-1 autocorrelation coefficient as the measure of resilience based on Critical Slowing Down theory. The results are suggestive but very noisy and require a lot of assumptions to equate to a loss of ecosystem resilience. Since the authors also show that vegetation cover is increasing at the same time the results don't appear strong enough to merit any change in our discussion.
2	7	2.1.3, para. 2	Cheng did NOT report "increased plant growth"; they reported increased GPP. The distinction is fundamentally important, has been recognized for decades, and is completely ignored in this chapter. Cheng et al. did refer to an increase in Net Primary Production as well, but you are correct they focused on Gross Primary Production. The sentence has been rephrased "Similarly, Cheng *et al.* (2017) noted that increased Gross Primary Production from 1982 to 2011 due to rising…" and GPP has been added to the Glossary. More generally since GPP and NPP are closely correlated, the use of "plant growth" is suitable.
2	6-7	2.1.3	This material is repeated in chapter 9 where it belongs. Here, it would be more appropriate to focus on how eCO2 interacts with drought on ecosystem response (e.g., 10.3390/atmos12020212**)** We tried to avoid repetition but there is some. We discuss drought in Ch 8: since we don't see global and US trends, the issue of declining CO2 fertilization during droughts isn't a key issue at this point.
3	19	3.2.2, last para.	Regarding the uncertainty in the land sink, a primary reason for this uncertainty is that the primary response of photosynthesis to CO2 does not predict C sequestration because of strong interactions between CO2 and climate, nutrients, stand dynamics, and other factors. That is why the almost complete focus in this report on crop plants and plant responses in greenhouses does not inform us about "CO2 uptake by land processes" We aren't making any strong claims about the land sink, we only report the results in the Global Carbon Project. Not sure if the reviewer is challenging them or not.
9	104	all	This chapter is silent on agricultural effects on atmosphere and climate. Sokal and Kachel 2025 (10.3390/en18092272) conclude: "The current study demonstrated that agricultural activities significantly contribute to the emissions of three main greenhouse gases: carbon dioxide, nitrous oxide, and methane." Emissions from the Ag sector are included in the IAM results discussed in Ch 11.

DOJ_00000697

9	105	9.2, para. 2	The section title is "Field studies…" but the next three paragraphs are primarily about responses of potted plants in growth chambers or greenhouses (with exception of Blandino, which was a field study and showed a much smaller response than the pot studies). There is an important reason that the field data cited in Blandino and in SoyFACE show a smaller response than data from the potted plants under artificial conditions. These data are barely relevant to the topic you are trying to address. FACE plot studies are field studies, and we also discuss other field studies. However, we also include some lab experiments. Heading changed to "Field and laboratory studies of CO2 enrichment."
9	105	9.2, para. 3, 4, 5	CO2Science.org website is a highly biased and unreliable website. They report on papers, or specific sentences in papers, that support their view and ignore conflicting reports or qualifying sentences. If there was another site that gathered that much data, we'd cite it. We'd need some evidence of actual bias to disqualify the CO2Science.org archive given the extent of its coverage.
9	105	9.2, para. 3	This is a report for the US. Why are you citing soybean studies in China when there is a major soyFACE study in Illinois? Yield in SoyFACE incresed in eCO2 but declined with increasing temperature (10.1093/jxb/erac503). eCO2 did not result in water savings as hypothesized but rather increased soil moisture depletion. (10.1098/rstb.2024.0230) The Chinese study is on point regarding CO2 enrichment. The first study referenced by the reviewer (10.1093/jxb/erac503) only subjected soybean to elevated temperature without varying CO2, so it isn't relevant to our discussion. The second reference is to a general literature survey which doesn't appear to say anything different from what our chapter says.
9	106	9.2, para. 2	Ainsworth et al, 2025 (10.1093/jxb/erac503) state: "Early season stimulation in biomass at elevated [CO2] more than offset lower stomatal conductance in crops, resulting in greater depletion of soil moisture, instead of water savings [30,31]. Wheat tiller survival and grain filling was also reduced by elevated [CO2] under dry conditions [32]. The CO2 fertilization effect was also significantly reduced by growth at elevated temperatures in FACE experiments, again suggesting that high atmospheric [CO2] may not offset the negative impacts of global warming [29]. Thus, it may be that, to date, elevated [CO2] and the resultant climate changes have had net positive effects on agroecosystem productivity, but as climate change intensifies, there will be a shift towards net negative effects as has been suggested for natural ecosystems [3]." Our summary statement on the Ainsworth review is accurate regarding the CO2 effect. They raise the question of compound effects from simultaneous changes in CO2 and temperature. That topic is taken up in the discussion of the NBER study and Section 9.3

DOJ_00000698

9	107	1st para.	Another study that should be cited is Hultgren et al, 2025 (10.1038/s41586-025-09085-w). "For all crops except rice, we estimate that warming will likely reduce global yields by 2050 (probability of loss ranges from 0.701 (sorghum) to 0.946 (wheat)…" "We estimate that global production declines 5.5 ×10^14 kcal annually per 1 °C global mean surface temperature (GMST) rise (120 kcal per person per day or 4.4% of recommended consumption per 1 °C; P < 0.001). We project that adaptation and income growth alleviate 23% of global losses in 2050 and 34% at the end of the century (6% and 12%, respectively; moderate-emissions scenario), but substantial residual losses remain for all staples except rice." Regions with moderate average temperatures tend to suffer the largest yield losses. "Adjusting for CO2 fertilization does not qualitatively alter the structure of our findings ... but it does reduce the central estimate for end-of-century yield losses by 5.0– 9.5 percentage points... and increases the likelihood of positive aggregate effects." The Hultgren study came out after our draft had been complete. The headline results, which generated massive publicity, were based on RCP8.5 with no CO2 fertilization. One of our other reviewers wondered why we focused so much on the deficiencies of RCP8.5 when everyone knows it's a marginal case – this study is a good illustration of why. Figure 3 in Hultgren
9	108	1st	Reference to Ziska paper greatly mischaracterizes it. Ziska clearly indicates an effect of eCO2 on nutritional quality, but he indicates there is uncertainty in some of the mechanisms behind that response, including the simple dilution hypothesis. He states up front: "However, it is the direct effect of rising [CO2] on plant chemistry and stoichiometry that represents a continuing threat to the nutritional integrity of both human and animal systems." Ziska doesn't dismiss CO2, but he points out that nutrient dilution has also been observed under historical conditions in which CO2 was likely not the driver. Sentence rephrased "as is the evidence that nutrient dilution observed to date is entirely attributable to higher CO_2"
9	108	9.4, para. 1	Evidence for nutritional decline under eCO2 is widespread: Toreti et al, 2020 10.1038/s43016-020-00195-4) "A meta-analysis of 228 pairs of experimental observations on barley, potato, rice and wheat reported reductions in protein concentrations ranging on average from –15.3% to –9.8% under eCO2, while the reduction was relatively small (–1.4%) in soybean." AND Ainsworth et al 2025: "The positive 'CO2 fertilization' effect on crop yield is complicated by a decrease in many nutrients in elevated [CO2]. An analysis of 130 varieties of plants found that elevated [CO2] decreased the concentration of 25 important minerals by 8% on average, and the carbohydrate to mineral ratio was increased in these plants." We don't dispute any of this; it corresponds with what we say.
9	109		URL for Taylor and Schlenker paper is incorrect. It should be https://www.nber.org/papers/w29320. "papers" not "paper. Was this report peer reviewed? I cannot find it in a peer-reviewed journal. Thanks for the correction. We don't think it has appeared in print anywhere other than the NBER series.

DOJ_00000699

12	129		This chapter is highly distressing, but I suppose it encapsulates the whole thesis of the document. Apparently, there is no point in policies to reduce emissions (or make the necessary changes in energy policy to accomplish emission reductions) because it will make no difference to the atmsoopheric CO2 concentration or climate. So why bother? Would you have said this in 1970 (CO2= 326), 1990 (CO2 = 354 ppm), or 2010 (CO2=390)? Probably so. And in 30 years when CO2 is 500 ppm, will it be fair to look back and evaluate your apparent call for inaction in the statement here "And even if global emissions were to stop tomorrow, it would take decades or centuries to see a meaningful reduction in the global CO2 concentration and hence human influences on the climate." But I suppose this attitude is justified if there is no adverse consequence and the only importaant effect of rising CO2 is to make little plants in greenhouse grow bigger (e.g., Fig. 2.3), and indirect effects on heat stress, drought, fires, sea level, etc. aren't worth discussing. The chapter rehearses some straightforward quantitative aspects of mitigation without making any policy recommendations. The reviewer is calling attention to actual problems finding mitigation strategies with positive net benefits.

DOJ_00000700

Ch	Page	para	Comment or Suggested Edit
1	2	full text	This chapter points out that the primary concern around human emissions of CO2 is that it changes the radiative balance of the atmosphere. The chapter also makes the points that CO2 has no toxicological effects on humans at current atmospheric levels, and that CO2 is necessary for photosynthesis, with the potential to stimulate plant growth at higher concentrations. These points are well-established scientific facts. Yes and experts know them but non-experts aren't necessarily aware of them.
2	3	3	It would be more reflective of the literature to say here that "Many studies over the past decade have confirmed a global greening pattern (increase in LAI) attributable to rising CO2 levels, changes in climate, changes in nitrogen deposition, land cover change, and other factors." We have added "in part" to sentence.
2	3	3	While the Zhu et al. 2016 study did find that 70.1% (+/- 29.4%) of the integrated global change in LAI was attributable to changes in CO2, most of the observed change in LAI is concentrated in the tropical forest regions of South America, Africa, and Indonesia, as shown in this report's Figure 2.1, reporoduced from Zhu et al. In terms of the fraction of global land area influenced most by the factors considered in Zhu et al. 2016, effects on LAI from changing climate is the dominant factor (positive effects for 28.4% of land area plus negative effects on 4.7%, for a total area with dominant climate influence of 33.1%), followed by other factors not represented explicitly in the study or in the models (positive effects on LAI from other factors over 25.0% of land area plus negative effects over 5.3%, for a total area with other factors as the dominant effect of 30.3%), and then CO2 effects (23.2% of land area dominated by positive effects and 0.1% with negative effects, for a total of 23.4%). Since the report is focused on the U.S. it would be helpful toindicate the global context for the numbers reported. We have added new text "Other contributors included land-use changes, warming and nitrogen. The fraction attributable to CO2 was largest in the tropics; other factors played more dominant roles in CONUS."
2	3	3	The dominant factors related to changes in LAI over the U.S. (including Alaska) are land cover change (+LCC), climate effects (+CLI), other factors (+OF and –OF), and then CO2 (+CO2). There are more extensive regions where +CO2 is the dominant factor for the boreal forest zone in Canada. Given that, and given the explicit focus of the report on the U.S., it would be useful to call out in this section that the global greening pattern has distinct geographic variation in driving factors, and that over the target geography of the U.S. it seems to be dominated by factors other than increasing CO2. See my powerpoint slide 1 for a zoom on the area of interest from the Zhu et al. 2016 paper. Addressed with new sentence: CO2 fertilization effects are influenced by local temperature and nutrient and water availability, all of which vary regionally.
2	3	4	"Zheng et al. (2017) confirmed the pattern..." should be modified to say "Zhen et al. (2017) confirmed the pattern of observed greening..." As written, and in the context of the previous paragraph, the current text suggests that Zheng et al. 2017 confirmed the pattern of greening being related mainly to increased CO2, a factor which was not examined in their study. Changed: confirmed the pattern of greening, noting that over thirty years it had added 8 percent…
2	3	4	Without the addition of the appropriate context in the preceeding paragraph (my notes 3, 4, and 5) the remainder of this paragraph could be misinterpretted to mean that the impacts of greening on air temperature are attributable back to a positive effect of CO2 on greening. Rewording has addressed this.

2	3	4	The sentence "Greening has been observed globally but Chen et al. (2019) noted that China and India were exploiting it through land management changes" is misleading. Chen et al. (2019) shows that China and India are *causing* the observed greening in large areas by intentionally increasing the land area occupied by forests (China)and increases in harvested area in croplands, mainly due to multi-cropping, heavy fertilizer use, and expanded irrigation (China and India). It would be more accurate to say "Greening has been observed globally, but Chen et al. (2019) represent a disproportionate fraction of the total greening trend, accomplished through intentional increases in forest area (China), and expansion of multi-cropping, fertilizer use, and irrigation in croplands (China and India)." Changed: “Greening has been observed globally. Chen et al. (2019) show that in China and India much of it is driven by land management changes”
2	3	3 and 4	Given the changes suggested in these two paragraphs, it raises the question of whether the section title (CO2 and global greening) is itself misleading. That title wrongly suggests that all the content to follow is reflective of a direct influence of CO2 on the observed global greening trends, when the literature presents a much more *nuanced* interpretation. **T**ltle changed to “CO2 as a contributor to global greening”
2	3	3 and 4	It would be worth noting in this section that the multiple remote sensing-based datasets for LAI changes have remarkable differences, especially when comparing the figure 2.1 reproduced from Zhu et al. 2016 with the MODIS-based data record from Chen et al. 2019 (their figure 1). That means it is difficult to place a lot of confidence in the attribution of changes in different regions to different factors. See my powerpoint slide 2 for a comparison of the four datasets used in Zhu et al. 2016 and Chen et al. 2019. Thank you for this information. It is an interesting point but gets into more specialized detail than is necessary for this report.
2	3	5	The authorship for the Haverd et al. 2020 citation is not correct in the References section for this chapter. The correct citation is: Haverd, V., B. Smith, J. G. Canadell, M. Cuntz, S. Mikaloff-Fletcher, G. Farquhar, W. Woodgate, P. R. Briggs and C. M. Trudinger 2020. Higher than expected CO2 fertilization inferred from leaf to global observations. Global Change Biology 26(4): 2390-2402 DOI: https://doi.org/10.1111/gcb.14950. Corrected
2	3	5	A more recent and more comprehensive study (Keenan et al. 2023) reexamined multiple data constraints and concluded that the model used in Haverd et al. 2020 (CABLE) is outside the likely range of CO2 fertilization effects, with jigher CO2 fertilization than indicated by multiple independent constraints. At the very least this more recent paper should be cited in the report, with text indicating that the central estimate from the TRENDY models is more likely to be in the range of observational constraints than is the CABLE result. As it stands the report suggests that the latest science indicates that most models have underestimated the fertilization effect, and the literature doesn't currently support that conclusion. See: Keenan, T. F., X. Luo, B. D. Stocker, M. G. De Kauwe, B. E. Medlyn, I. C. Prentice, N. G. Smith, C. Terrer, H. Wang, Y. Zhang and S. Zhou 2023. A constraint on historic growth in global photosynthesis due to rising CO2. Nature Climate Change 13(12): 1376-1381 DOI: 10.1038/s41558-023-01867-2. Added sentence: However Keenan et al (2023) estimated a lower fertilization rate more in line with models.

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2	4	1	The attribution analysis in the Chen et al. 2024 paper is very sensitive to the choice of multiple regression vs. partial correlation (their figures 3 vs S7, respectively), and in both cases they seem to misattribute the significant increases in LAI in India and China to CO2 rather than to changes in landcover and cropping practices. This kind of regression-based attribution is less informative than the model-based inference used for example by Zhu et al. 2016. The description of sensor calibration issues in this paper is also very cursory. It would probably be better to refer to the review paper of Piao et al. 2020 to support the claim of continued greening. Piao, S., X. Wang, T. Park, C. Chen, X. Lian, Y. He, J. W. Bjerke, A. Chen, P. Ciais, H. Tømmervik, R. R. Nemani and R. B. Myneni 2020. Characteristics, drivers and feedbacks of global greening. Nature Reviews Earth & Environment 1(1): 14-27 DOI: 10.1038/s43017-019-0001-x. Thank you for the comment. We have taken out the details about the Chen et al. analysis and say simply "Piao et al. (2020) and Chen et al. (2024) report that the greening trend continues with no evidence of slowdown, and CO2 fertilization remains the dominant driver"
2	4	2	The section 2.1.2 (Photosynthesis and CO2 levels) lacks coherence. It seems to be a collection of uncontroversial points about the ability of increased CO2 concentration to stimulate plant growth and reduce water loss through stomates. Figure 2.2 seems intended to show that the current levels of CO2 are not high compared to levels experienced in Earth's deep geologic past. A balanced treatment of the topic might call out the rate of change in CO2 concentration from human-caused emissions, and how both that rate and the absolute levels diverge radically from rates of change and ranges of variability over the past hundreds, thousands, and hundreds of thousands of years. See my powerpoint slide 3 for an example set of figures that might be included. In response to another reviewer, we have added the sentence "While the modern rate of change in CO2 is likely high compared to all prior intervals, the geological evidence is that plants and animals evolved under much higher CO2 levels than at present."
2	7	4	The report suggests that the topics of CO2 fertilization and increased water use efficiency are not adequately treated in recent IPCC reports. In IPCC's AR6 WG I report there is an entire chapter devoted to an assessment of carbon cycle processes (Chapter 5, Global Carbon and Other Biogeochemical Cycles and Feedbacks). This is precisely where one would expect to find information about CO2 fertilization and water use efficiency. In the Executive Summary for the chapter is the following bolded headline: **Increases in atmospheric CO2 lead to increases in land carbon storage through CO2 fertilization of photosynthesis and increased water use efficiency (high confidence).** The associated Executive Summary text includes refernce to two figures, three chapter sections, and a cross-chapter box all dealing directly with this topic. The Executive Summary text also references the important topic of nutrient dynamics and their interactions with fertilization and ecosystem-climate feedbacks, a critical nuance of the interaction of CO2 and vegetation productivity that is ignored in the report reviewed here. We acknowledge that the topic is addressed in the body of IPCC reports. But we draw attention to its omission from summary documents.

DOJ_00000703

2	8	2	Section 2.2.2 (Coral reef changes) has a strong focus on past examples of early investigations that are later updated. There is also a note about the difficulty of publishing negative results, with a quote that this pattern "is true across all of science". Given the objective of this report, I suggest a shift in tone away from complaints about the kinds of papers that do and don't receive media attention, and instead highlight the latest synthesis of results about the likely future of coral reefs. A relatively recent synthesis paper (Cornwall et al. 2021) in a well-respected journal (PNAS) based on collated data from 233 locations worldwide projects that 37% of reefs will stop acreting and thus fail to keep up with sea level rise by 2050 under the low eimissions RCP2.6 scenario, and no reefs would be able to acrete at a rate to stay ahead of sea level rise by 2100 under either RCP4.5 or RCP8.5. This analysis finds that most of the loss of net acretion rate is due to bleaching events, and a minority of the impacts are due to "direct physiological impacts of ocean warming and acidification on calcification or bioerosion". C.E. Cornwall,S. Comeau,N.A. Kornder,C.T. Perry,R. van Hooidonk,T.M. DeCarlo,M.S. Pratchett,K.D. Anderson,N. Browne,R. Carpenter,G. Diaz-Pulido,J.P. D'Olivo,S.S. Doo,J. Figueiredo,S.A.V. Fortunato,E. Kennedy,C.A. Lantz,M.T. McCulloch,M. González-Rivero, [...] & R.J. Lowe, Global declines in coral reef calcium carbonate production under ocean acidification and warming, Proc. Natl. Acad. Sci. U.S.A. 118 (21) e2015265118, https://doi.org/10.1073/pnas.2015265118 (2021). This is a model projection study whereas for the very limited purpose of this section we are focusing on current and historical observations.
3	14	1	The study by Conolly et al. 2021 uses a linear regression approach to estimate the amount of variability in surface temperature trends that could be explained by total solar irradiance time series. Their approach is to first model the temperature trend with TSI as the dependent variable, and then compare the residuals from that fit to anthropogenic forcing factors. This is an obviously biased approach, and in fact a full paper was published the following year (in the same journal) laying out the erroneous methods and the faulty conclusions they produce (Richardson and Benestad 2022). Richardson, M. T. and R. E. Benestad 2022. Erroneous use of Statistics behind Claims of a Major Solar Role in Recent Warming. Research in Astronomy and Astrophysics 22(12): 125008 DOI: 10.1088/1674-4527/ac981c. While we agree with R&B that a partial regression is biased unless the regressors are orthogonal, Connolly et al. replied in 2023 at https://iopscience.iop.org/article/10.1088/1674-4527/acf18e&quot in which they used updated AR6 data and reproduced their main result using multiple regression. However they also emphasized that it is only one of many possible results depending on choice of solar proxy and surface T record,
3	18	1	Section 3.2.2 (The carbon cycle relating emissions and concentrations). There is no new information or analysis presented in the chapter, and it relies heavily on Global Carbon Project information. Figure 3.2.3 is described as showing a seven-fold difference in the recent trend in land carbon sink estimates across land models, and this is given as a potential driver of uncertainty in future carbon cycle and climate change predictions. Variation among models is well known and is one of the reasons exercises like CMIP and GCP rely on multi-model ensembles when assessing the state of the science. The distribution of results looks fairly typical in this diagram, with a strong central value around 1.3 to 1.3. We're not claiming to have added new information, just reviewing what's out there.

DOJ_00000704

12	129	3	The following sentence is misleading: "And even if global emissions were to stop tomorrow, it would take decades or centuries to see a meaningful reduction in the global CO2 concentration and hence human influences on the climate." It is true that bringing global emissions immediately to zero would not reduce CO2 concentrations on short timescales. It is not true that this same scenario means no reduction in human influence on the climate. We must compare the zero emissions scenario to something, and the most meaningful comparison is the current trajectory of **increasing** emissions and the resulting **super-linear** increase in concentration. So by reducing emissions to zero we clearly avoid the expected increases in concentration and the expected increases in radiative forcing together with increased near surface air temperature and all the other expected consequences. So our change in action - going to zero emissions - does in fact have an immediate and gowing human influence on the trajectory of the climate system. That is not an argument for reducing our emissions to zero tomorrow, it is just an argument for logic and clarity in how we talk about consequences of different actions. The sentence in the text is correct. It's also true to say that going to zero emissions would, over time, open up a widening gap between observed and counterfactual. But realistically we are only looking at marginal changes. The stock-flow mismatch is one reason IAMs have not recommended going to zero emissions.
12	129	5	Regarding the sentence "The practice of referring to unilateral U.S. reductions as "combatting climate change" or "taking action on climate" therefore reflects a profound misunderstanding of the scale of the issue." This makes the dubious assumption that when people refer to "combating climate change" or "taking action on climate" they are ignorant of the scale of the problem. Instead, it is probably more justifiable to assume that it is well-understood by most people who advocate for these local and national changes that the major emitters must act together to make a big difference in global emissions. It is at least worth considering, in the context of this report, that a path toward action at the necessary scale will require local and national action from a broad consortium, and that individual advocacy is a useful and necessary starting point for shifting the inertia of global policies. Sentence modified to read "The practice of referring to unilateral U.S. reductions as "combatting climate change" or "taking action on climate" on the assumption we can stop climate change therefore reflects a profound misunderstanding"

DOJ_00000705

Ch	pg	para	Comment or Suggested Edit
Overarching	Overarching	Overarching	• I would like to thank the authors for the opportunity to provide comment on this report. Providing decision-makers with information about the impacts of carbon dioxide emissions on the U.S. climate is critical as they face consequential decisions about the future of energy, agricultural, and environmental policy. Assessments of the science such as IPCC reports and the NCA benefit from undergoing robust review including expert review, public review, and government review with review comments and responses made publicly available. Similarly, important government reports and regulations undergo inter-agency review and are published in the Federal Register for a full notice and comment process and publish a public response to comment. While these processes are far from perfect, they offer the opportunity for improvement and help lend authority to the final products, and I highly encourage you to undertake a similar robust and open peer review process for this report to enhance the report's credibility in the eyes of decision-makers and the public.
Executive Summary	viii	1	• There is a disconnect between the stated intent of the report by the authors in the preface, "whether carbon dioxide emissions endanger the U.S. public," and this executive summary, as well as the organization of the report. Would suggest aligning by either reframing the focus in the preface to better match the organization of the report, or better aligning the report organization with the stated focus. Preface has been reworded and the statement eliminated. We have also changed the title to clarify this
Preface	ix	3	• "While the report is intended to be accessible to non-experts, we have omitted some introductory or explanatory material that can easily be accessed elsewhere. Nor have we attempted to survey entire literatures related to the topics covered." • While this approach is understandable given the time constraints this report was produced under, given the level of visibility this report will have, it potentially opens up the report to criticism of being misleading by omission – focusing on areas where the authors disagree with the broader scientific literature and omitting areas large areas that are known about climate where there is less disagreement. See our response to the previous comment and revisions to paragraph 2.
Preface	ix	3	• "We have focused as much as possible on literature published since 2020 and referenced previous IPCC and NCA assessment reports. We have also used data through 2024 where possible." • This is a good approach for this report; however, much of the literature cited is from pre-2020, and many of the references to IPCC and NCA reports are to older reports (e.g. NCA 4 and IPCC AR 4&5) instead of NCA 5 and IPCC reports from the 6th assessment cycle. In these sections that heavily cite this older literature, it is not clear if the newer literature does not address these points or if the issues raised in the older literature are resolved or significantly changed in the newer literature. We have included reference to previous assessment reports where the analysis is insightful and not superseded by later reports. We note that we regard NCA4 as far more credible than NCA5

Preface	ix	3	• The IPCC's mandate is to assess the scientific literature comprehensively, including a range of views, and report disagreements. This report has a tendency to selectively quote the IPCC focusing on disagreements and excluding areas where scientists agree. This approach risks giving a misleading picture of the state of the science through omission. A possible way to address this is to have a section summarizing areas of agreement by pointing to all statements of fact and high confidence statements from IPCC AR6 before digging into the more controversial areas with disagreement. This could be a short discussion about areas of agreement up front before explaining the focus of this report on these areas of disagreement, with the IPCC statements of fact and high confidence statements included in an appendix. • The report also includes only a very small subset of the literature since 2020. The authors should describe the approach to how they selected the literature included, and if possible, point to any systematic ways excluded literature could lead to different conclusions. • It is also notable that there a fair amount of new analysis in this report done by the authors that has not yet been peer reviewed. It would be good to flag these spots with a note about why these are needed while other related peer reviewed articles are excluded. This is addressed to some extent in the revised Preface
1	2	1	• If the goal of this report is to discuss links between CO2 and climate, this is an odd way to begin the report with a focus on differences between CO2 and criteria air pollutants. It clears up a confusion of language that persists
1	2	1	• "It is an issue of concern because of its potential effects on the global climate, a complex issue that occupies much of this report." Suggest deleting the word potential as the existence of the effect is not disputed. Deleted: "potential"
1	2	4	• "But the primary concern about CO2 is its role as a greenhouse gas (GHG) that alters the earth's energy balance." Would add "warming the planet" to the end of this sentence as the qualitative effect is not debated and the concern is not about the energy balance itself but about the warming effects of the imbalance. Added: "warming the planet"
2	3	1	• "The recent decline in pH is within the range of natural variability on millennial time scales. Most ocean life evolved when the oceans were mildly acidic. Decreasing pH might adversely affect corals, although the Australian Great Barrier Reef has shown considerable growth in recent years." • Note that the IPCC Special Report on the Ocean and Cryosphere in a Changing Climate (SROCC) finds that pH decline has very likely emerged from natural variability. SROCC SPM A.2.5, "Open ocean surface pH has declined by a very likely range of 0.017–0.027 pH units per decade since the late 1980s, with the decline in surface ocean pH very likely to have already emerged from background natural variability for more than 95% of the ocean surface area." We have left this out since it relates to attribution, which is beyond the scope of what we are addressing in this chapter
3	15	3	• "Instead, the IPCC has created various sets of scenarios meant to span a plausible range of possibilities" • Suggest changing "created" to "assessed" as the scenarios are created by the science community not the IPCC. We have changed the wording to "used"
3	16	4	• "The IEA trends, which are based on plausible extrapolations of current economic and demographic trends, run below the entire envelope of RCP projections, implying not only that RCP8.5 is dubious, but that even lower emission scenarios are unlikely." • Burgess compares IEA to the two highest SSP-RCP scenarios, not to the full range. The last sentence of the paragraph is incorrect – the range in Burgess is only no climate policies which doesn't include the lower RCPs. The Burgess diagram is poorly-labeled and hard to understand. The text has been revised added a reference to Pielke Jr et al 2022 which has a better presentation.
3	17	2	• "As of 2023, global CO2 emissions have been tracking well below SSP7.0 and are even below SSP2-4.5." • Note that near-term emissions are not necessarily a good predictor of long-term emissions, as the latter will depend on changes in population, demographics, technology, and policy that do not have the same influence on near-term emissions. Noted

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3	22	6	• "In summary, while there is clearly warming in the land record, there is also evidence that it is biased upward by patterns of urbanization and that these biases have not been completely removed by the data processing algorithms used to produce climate data sets." • Quantitative info would be helpful here. How large is the warming? How large might the bias be? This is a topic that needs revisiting. The quantitative estimates are 15+ years old
4	26	1	• The Chapter Summary doesn't really capture the full tax of the chapter. Would suggest: Defining ECS/TCS, reporting values for ECS and uncertainties/methods, then reporting values for TCS, preferably with a sentence on what those values imply The terms are defined in the chapter
4	26	2	• "This raising of the lower bound is less justified; evidence since the AR6 finds the lower bound of the likely range to be around 1.8°C." • This isn't really discussed comprehensively in the chapter. It is discussed, in context of Nic Lewis' research
4	26	3	• "The climate's response to increasing concentrations of CO2 is central to the scientific debate on anthropogenic climate change" • Suggest rewording this to, "The magnitude of the climate's response…" As currently worded it could be a bit misleading since the qualitative effect (i.e. increasing CO2 concentrations lead to increases in global average temperature) is not disputed – the uncertainty is around the magnitude of the effect. Reworded
4	26	6	• The text sites Dayaratna (2016), but this should be a reference to Dayaratna (2017) as listed in the reference section. Fixed
4	26	6	• "If ECS is very high (above 4.5°C) immediate aggressive emission controls become more imperative, whereas no CO2 emission controls are economically justifiable for ECS below 2.0°C (Dayaratna et al. 2016, 2020)." • This could use additional clarification as there are low and now carbon technologies that can be economically justified based on cost of energy alone, depending on technology, location, etc. We have left as is. We are not aware of low or new carbon technologies that are affordable and scalable. Likewise. If energy conservation pays for the low carbon tech people would have been adopting them already.

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4	26	6	• "Obtaining a precise estimate is impossible, so policy making needs to account for the uncertainty." • The Social Cost of CO2 (SC-CO2) as used by the USG in regulatory impact analyses has always accounted for uncertainties in the ECS. EPA (2016) used a probability distribution for the ECS calibrated to IPCC AR4 findings (the most recent values available at the time) to harmonize the approach for the three models used (FUND, DICE, and PAGE). EPA (2023) updated the SC-CO2 in response to NAS recommendations (NAS 2017) to include a much fuller representation of the uncertainties in both ECS and TCR, and utilized a modular approach incorporating the Finite amplitude Impulse Response (FaIR) climate model, a reduced complexity climate model, with ECS and TCR distributions calibrated to IPCC AR6 to represent this uncertainty. • The Dayaratna (2017 & 2020) papers referenced here analyze sensitivity of a subset of the older models used in EPA (2016) to just ECS estimates. It would be helpful to address the advances in the broader literature that are discussed and represented in EPA (2023) as the focus of this report is on literature published since 2020. • EPA (2016) "Technical Support Document: Technical Update of the Social Cost of Carbon for Regulatory Impact Analysis Under Executive Order 12866 Interagency Working Group on Social Cost of Greenhouse Gases, United States Government." https://www.epa.gov/sites/default/files/2016-12/documents/sc_co2_tsd_august_2016.pdf • EPA (2023) "Supplementary Material for the Regulatory Impact Analysis for the Final Rulemaking, 'Standards of Performance for New, Reconstructed, and Modified Sources and Emissions Guidelines for Existing Sources: Oil and Natural Gas Sector Climate Review' – EPA Report on the Social Cost of Greenhouse Gases: Estimates Incorporating Recent Scientific Advances." Docket ID No. EPA-HQ-OAR-2021-0317. https://www.epa.gov/system/files/documents/2023-12/epa_scghg_2023_report_final.pdf • NAS (2017) "Valuing Climate Damages. Updating Estimation of the Social Cost of Carbon Dioxide" https://nap.nationalacademies.org/catalog/24651/valuing-climate-damages-updating-estimation-of-the-social-cost-of Most of the topics are touched upon in Ch 11. The newer EPA approach (e.g. the FaIR model) don't reflect a fundamentally different approach than before. Will discuss below.
4	28	2	• "Because of concerns about model tuning and the high sensitivity to cloud parameterizations, the IPCC AR6 (2021) did not rely on climate model simulations in their assessment of climate sensitivity, relying instead on data-driven methods." • AR6 WGI 7.5.5 states this a little differently. IPCC's assessment wasn't "directly informed" but "ESMs remain essential tools." Our statement is ok as is
4	29	3	• "For AR6, the IPCC placed primary weight on the results of Sherwood et al. (2020)…" • The IPCC assessed a large number of studies, not just Sherwood (2020). Our statement is ok as is. Sherwood et al was predominantly relied upon
5	32	1	• It would be helpful for the reader for this chapter to start with a summary figure (e.g. like IPCC AR6 WG1 – SPM.1 or Fig. 3.4). Currently, the chapter jumps right into details that will be difficult for anyone who is not a climate scientist or already versed in these issues to understand or interpret. Too late in the process to add a new figure
5	33	Figure	• "Figure 5.1 CMIP6 Average surface temperature range across 33 models and standard deviation using SSP5-85 scenario." • SSP5-85 is an excessively high scenario that is not representative of current expectations of emissions projections. Suggest changing the figure for on with data from a less misleading and more representative scenario. The use of 8.5 doesn't make much difference given high spread for historical period, but we agree this should be changed for a subsequent version of the Report

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5	34	1	• There have been extensive published comments and responses on the approach used in Scaffeta (2023). Can these be reflected here? • G.A. Schmidt, G.S. Jones, and J.J. Kennedy, "Comment on "Advanced Testing of Low, Medium, and High ECS CMIP6 GCM Simulations Versus ERA5-T2m" by N. Scafetta (2022)", Geophysical Research Letters, vol. 50, 2023. http://dx.doi.org/10.1029/2022GL102530 • N. Scafetta, "Reply to "Comment on 'Advanced Testing of Low, Medium, and High ECS CMIP6 GCM Simulations Versus ERA5-T2m' by N. Scafetta (2022)" by Schmidt et al. (2023)", Geophysical Research Letters, vol. 50, 2023. http://dx.doi.org/10.1029/2023GL104960 • Z. Hausfather, K. Marvel, G.A. Schmidt, J.W. Nielsen-Gammon, and M. Zelinka, "Climate simulations: recognize the 'hot model' problem", Nature, vol. 605, pp. 26-29, 2022. http://dx.doi.org/10.1038/d41586-022-01192-2 • S. Jain, A.A. Scaife, T.G. Shepherd, C. Deser, N. Dunstone, G.A. Schmidt, K.E. Trenberth, and T. Turkington, "Importance of internal variability for climate model assessment", npj Climate and Atmospheric Science, vol. 6, 2023. http://dx.doi.org/10.1038/s41612-023-00389-0 The Schmidt et al paper is a comment on a different paper of Scaffeta's and focuses on his t-statistic, which isn't pertinent to the paper we cite (from Climate Dynamics). Regarding the Jain et al paper, Scaffeta uses ensemble ranges within each ECS type and doesn't simply rule models out but shows that some perform well for TAS. Relevance of the Hausfather et al paper is not clear.
5	34	4	• "Spencer (2024) has also provided a useful summary of the Model-Observation mismatch by comparing trends in surface temperature data products with those in individual climate models, as summarized in Figure 5.3; most climate models show substantially more warming than the observations since 1979." • It is worth noting that IPCC projected temperatures do not use all models and instead focus on those that best reproduce observations. So while some models may show warmer or cooler temperatures than observations, that does not imply that projections from large assessments reflect those biases. Our text speaks to the collection of CMIP6 climate models; some of those with the largest amount of warming are widely used models from the US and UK
5	37	3	• "Hence, we assess with medium confidence that CMIP5 and CMIP6 models continue to overestimate observed warming in the upper tropical troposphere over the 1979–2014 period by at least 0.1°C per decade," "Notably, despite the accumulation of evidence of excess model warming the IPCC assigns only medium confidence to the existence of a warming bias." • This reflects a more general issue with IPCC confidence statements where the inclusion of a quantification reduces the confidence they include. Here the full statement with the quantification of 0.1C per decade is assigned medium confidence whereas a statement about the existence of the bias without a specific quantification would receive higher confidence. Noted
5	39	Figure 5.7	• Does this update with data through 2024 use the same models that Christy and McNider (2017) used, or does it use updated versions for the models as well? This would be helpful to clarify here and in other places where figures are produced with updated data. Excellent catch. Fig. 5.7 uses CMIP6 models this will be stated in the caption as an update of Christy and McNider with CMIP6 output.
5	39	3	• "The IPCC AR6 did not assess this issue." • Was this assessed in IPCC AR5? Many of the citations here could have been assessed then. Is there any more recent evidence on these issues that should be referenced here? IPCC has never addressed this issue with rigor, but does reluctantly notes the discrepancy.
5	40	1	• Are there more recent papers or data available? All the info here is AR6 or pre-AR6, but more recent years have shown more surface warming. It would be interesting to show stratospheric temperatures for these more recent years as well to see how this relationship holds. Santer et al. (2025) has been added.

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5	40	5	• Trends in snow cover depend on both changes in precipitation and changes in temperature. It would be helpful if these were discussed separately rather than showing the net effect for one region/season. Context for statement is that the models get it wrong
6	47	1	• This chapter relies solely on observations and does not include other lines of evidence, it would be helpful to discuss what these other lines of evidence indicate to avoid introducing potential biases (e.g. what do process based lines of evidence show?) Yes we rely primarily on observations. We have added some text regarded process-based analyses, notably in the section on hurricanes
6	47	1	• The chapter summary does not fully capture the chapter or the science. Suggest talking about the extremes affected by climate, the extremes not affected by climate, and those where the data isn't sufficient to establish a trend. We think our summary is appropriate
6	47	3	• "Over geologic time the climate system has generated an (essentially) infinite variety of weather patterns and extremes…" • Just because an event occurred before humans does not mean humans are not influencing the frequency or intensity of such events now. Additionally, if something has happened in the geologic record, but humans have never experienced it before, they may not be prepared for such an event. Changes in frequency or intensity are precisely the issues discussed. Adaptation to extreme weather is a separate but important issue
6	50	Figure	• The figure heading has "@RyanMaue" in the title. Looks odd to have a social media handle in the figure. Is the source peer reviewed? We have added reference to an older publication by Maue that describes the analysis
6	52	4	• Insufficient data is different than no effects. It would be helpful to be clear in instances like this whether a conclusion is because the data supports it, or because there is insufficient data to say the opposite. This is covered in the last para of the section
6	53	Table	• Could you also show a similar table with hurricane precipitation? It is hard to get historical rainfall going very far back
6	53	5	• The last two paragraphs show findings from NCA4. With the interest in focusing on recent literature, what does NCA5 say about these issues? Does it not cover this issue, does it say the same thing, does it contradict this finding? NCA5 statements are discussed in the body of the text, see pp 57ff.
6	54	1	• The heading of section 6.3.1 is a bit misleading as this is partly driven by warmer winters and fewer cold days. For the CONUS, the heading is accurate as demonstrated with observational analyses
6	58	Figure	• Figure 6.3.5 shows the number of days greater than or equal to 95F in 6-year periods. Why show this in 6-year periods? That seems like an unusual choice. Would this look different with 5, 10, or 15 year periods? The time series is 126 years long, which is evenly divisible by 6. The point is to compress the depiction of interannual (i.e. natural) variability and examine slower changes. In our decimal system, 5 or 10 years is more commonly used, but with 126 years of data, we did not want to leave an "orphan" column (one with fewer years) compared with the entire time series. This is explained in the figure caption.
6	58	4	• "We measure "Heatwave Days" here as the count of all days in May-Sep each year that exceed the 90th percentile for that day and that lie within a period of at least six consecutive days." • Why six consecutive days? Would this look different for 5 days, a week, 10 days? Six days seems like an unusual period to pick. As noted in the text we use a metric defined in NCA4 for heat wave days. Regardless, whatever parametric choice is made (i.e. 5 days, 10 days, 85th percentile, etc.) the 1920s to early 1950s dominate the occurrence of heat wave days. Added: The pattern of results show below does not depend on the choice of reference period.)"

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6	58	4	• The dependence on and subsequent choice of reference periods is worrying. Can multiple reference periods be shown to show the dependence? There will be no change in the fundamental result no matter which reference period is chosen. If the entire period-of-record is used to calculate percentiles, there will be fewer percentile exceedences than if a cold reference period is chosen (as was done in NCA4). However, the shape of the outcome will be the same.
6	59	3	• "The NCA5 directs readers to the website https://www.globalchange.gov/indicators/heat-waves (USGCRP 2023)" • Broken link. The link was live when the report was written, but the Reviewer is correct that it is now broken. Fortunately, we included the figure from that link to demonstrate the unusual start date (1961) and the fact that the sample contained only large cities.
6	61	3 to 6	• This reads as a very selective analysis. With a very tight time constraint and the fact our analysis required the construction of serially complete datasets, we selected regions that were called out by NCA5 and/or the IPCC AR6 as unusual. In future versions we shall have more regions to examine (e.g. upper Midwest, Central Plains, Texas Hill Country).
6	67	2	• Is this section suggesting that climate change is causing the decrease in tornadoes? No, this section doesn't engage in attribution
6	68	7	• This is another place where it would be better to reference newer literature and NCA5 instead of relying on NCA4. What has changed since then? NCA5 mentions drought many times, but in anecdotal ways without metrics for testing. For example, NCA5 pg 1-23 states. *"Between 1980 and 2022, drought and related heatwaves caused approximately $328 Billion in damages (in 2022 dollars). Recent droughts have strained surface water and groundwater supplies, reduced agricultural productivity, and lowered water levels in major reservoirs, threatening hydropower generation."* This statement simply says that the demand for water was not met by the human-built systems which manage water supplies – there is no metric here that measures a change in the natural water supply. The statements on which we focus relate to whether the supply has been changing – a metric related to the climate system.
6	69	1	• Figure 6.7.1, is this the same indicator used in AR6? We have clarified the text to refer to meteorological drought. AR6 speaks mostly of "Agricultural and Ecological Droughts" which are defined in for various regions as "*Agricultural and ecological droughts are assessed based on observed and simulated changes in total column soil moisture, complemented by evidence on changes in surface soil moisture, water balance (precipitation minus evapotranspiration) and indices driven by precipitation and atmospheric evaporative demand".*, so we are unsure what specific metric is referenced." Elsewhere it simply uses the term "drought" or "Meteorological and Hydrological Drought." AR6 pg 1075 "A drought is a period of abnormally dry weather that persists for long enough to cause a serious hydrological imbalance (Glossary; Wilhite and Glantz, 1985; Wilhite, 2000; Cook et al., 2018). Most droughts begin as persistent precipitation deficits ('meteorological drought') that propagate over time into deficits in soil moisture, streamflow, and water storage (Figure 8.6), leading to a reduction in water supply ('hydrological drought'). Increased atmospheric evaporative demand increases plant water stress, leading to 'agricultural and ecological drought'. The best we can say is the AR6 used a different metric than shown in Fig. 6.7.1 that likely varied from region to region. However, Fig. 6.7.1 has high correspondence with drought-related impacts.

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6	69	3	• "In summary there is no evidence of increasing drought frequency or intensity in the U.S. or globally over recent decades." • This statement is not supported by the citations presented here. AR6 finds that there are trends in agricultural and ecological droughts and this section does not contradict that finding, so this general statement about there being no evidence of increasing drought frequency or intensity is misleading. • AR6 SPM A.3.2 – "Human-induced climate change has contributed to increases in agricultural and ecological droughts in some regions due to increased land evapotranspiration (medium confidence)." Footnote, "Agricultural and ecological drought (depending on the affected biome): a period with abnormal soil moisture deficit, which results from combined shortage of precipitation and excess evapotranspiration, and during the growing season impinges on crop production or ecosystem function in general (see Annex VII: Glossary). Observed changes in meteorological droughts (precipitation deficits) and hydrological droughts (streamflow deficits) are distinct from those in agricultural and ecological droughts and are addressed in the underlying AR6 material (Chapter 11)." We have added "meteorological" to last sentence
6	69	4	• "The IPCC has not provided an assessment of wildfires." • AR6 WGII SPM discuses wildfire, and WG1 SPM discusses fire weather. • AR6 WGII SPM – B.1.1, B.1.4, Fig. SPM.2, Fig. SPM.3, B.5.2, B.6.2, C.2.3, C.4.2, D.4.2, • AR6 WGI SPM – C.2.4 Restated: The IPCC has not provided an attribution analysis of wildfires
7	75	1	• "The largest sea level increases along U.S. coasts are Galveston, New Orleans, and the Chesapeake Bay regions" • How much? Are there quantifications? The figures show this
8	83	3	• "AR5 Working Group II (Cramer et al., 2014) makes the following statement:" • What does AR6 say on this topic? The science on attribution has evolved since AR5. The AR6 did not make an analogous statement, but the challenges haven't been resolved
8	84	6	• "There are three areas of substantive criticism of the IPCC's assessment of the causes of the recent warming…" • Are there citations that can be included here or are these criticisms attributed to the authors? The section describes this adequately
8	84	6	• "IPCC's policy-informing…" • This phrasing is a bit odd. IPCC reports are policy relevant but policy neutral. This phrasing the direct policy in some way. Deleted "policy-informing"
8	90	3	• "For comparison, the IPCC estimate of forcing from the increase in atmospheric CO2 compared to preindustrial times is approximately 2.2 W/m2 (Figure 3.1.2)." • This is comparing different time periods. Figure 8.2 includes data for 2023 and 2024, IPCC wouldn't include the most recent years since it was published in 2021. Suggest updating from the IPCC data to Forster et al. (2024) that updates these indicators. • Forster et al. (2024) "Indicators of Global Climate Change 2024: annual update of key indicators of the state of the climate system and human influence" https://doi.org/10.5194/essd-17-2641-2025 Updated
8	92	2	• "It is not easy to justify a new positive low cloud feedback that began emerging in 2015." • Explain why this is not easy? Added, "since there is no obvious feedback trigger starting in 2015" e

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8	93	4	• "Other columns of IPCC Table 12.12 report on whether anthropogenic signals are expected to emerge this century under RCP8.5, the most extreme forcing scenario. We have omitted these columns for several reasons." • Can this be done for RCPs other than 8.5? The point of these omitted columns in IPCC Table 12.12 was to show that for some extremes we may not see an effect now, but will in the future. As it is presented here it implies future changes won't matter. Agree 4.5 would have been better, but this is a query that should be directed to the IPCC
9	104	1	• IPCC AR6 WGII has an assessment of agriculture (both in the SPM and in Chapter 5), and the IPCC also has a special report on Climate Change and Land, that are more comprehensive, recent, and cover a larger range of the literature than discussed here. Please update this chapter to reflect these findings. Need a more specific point of challenge. Other reviewers have brought up specific topics that were either addressed by revisions or are already covered. I think this is one area that goes under the heading of critiquing the mainstream, based on peer-reviewed literature.
10	110	4	• Section 10.1 rightly points out that technological advances have substantially reduced losses from extreme weather events. We are better at forecasting, preparing for, and adapting to extreme weather than we were in the past, and these advances all help reduce impacts. However, our ability to do this in the future depends upon preparing for future changes – we can't simply assume adaptation will continue, we need to provide information on future risks and how those risks are impacted by climate change in order to inform continued technological advances and future adaptation. Noted
10	111	1	• "In May 2025 NOAA announced it has withdrawn the Billion Dollar Disaster product from publication (Pielke Jr., 2025)." • It would be better to cite an official government source from NOAA announcing this withdraw instead of a blog post commenting on it. Agreed, but this is the best information available from a well-published expert
10	111	2	• Losses from extreme weather and climate events are driven by climate risk (the physical events themselves), exposure to those risks (population and infrastructure impacted by these events), and adaptation to those events (technological advances in forecasting, warning systems, and resiliency). Understanding these risks requires disentangling these drivers in order to prepare for the future. Noted. Such a risk assessment is beyond the scope of this report
10	112	1	• There are additional citations that focus on the net effects of heat and cold related mortality that would be worth discussing and citing in this section. • EPA. 2024. Draft Technical Documentation for the Framework for Evaluating Damages and Impacts (FrEDI). U.S. Environmental Protection Agency, EPA 430-R-24-001. • Cromar et al., 2022. Global Health Impacts for Economic Models of Climate Change: A Systematic Review and Meta-Analysis. Ann. Am. Thorac. Soc. 19, 1203–1212. https://doi.org/10.1513/AnnalsATS.202110-1193OC • Hsiang et al., 2017. Estimating economic damage from climate change in the United States. Science 356, 1362–1369. • Mills et al., 2015. Climate change impacts on extreme temperature mortality in select metropolitan areas in the United States. Clim. Change 131, 83–95 . The Cromar meta-analysis included only 7 studies for the US all published before 2015, and not all of them examined both hot and cold extremes. We think the citations we have, which includes the EPA, are adequate.
10	113	7	• Section 10.3.2 has good points about the importance of energy affordability and how energy poverty impacts adaptation behaviors. Cong et al. (2022) is another good citation for this section. • Cong, S., Nock, D., Qiu, Y.L. et al. Unveiling hidden energy poverty using the energy equity gap. Nat Commun 13, 2456 (2022). https://doi.org/10.1038/s41467-022-30146-5 Citation added

DOJ_00000714

11	Chapter	Chapter	• Much of this chapter if focused on older literature on SCC and on applications that fall outside of how the USG has actually implemented SCC. This chapter would benefit from a more explicit focus on EPA (2023) as it represents the latest state of the literature on SCC, shows how the USG applies the SCC for regulatory impact analyses, shows how the USG updated the older IAG era SCC as represented in EPA (2016) in response to the recommendations in NAS (2017), shows how uncertainty is incorporated into SCC estimates, and discusses areas of the literature that are on the frontier, highly uncertain, and not ready to be incorporated into the official USG estimates. • As currently written much of this chapter is focused on these highly uncertain areas of the literature that are not incorporated into USG SCC estimates (e.g. tipping points, and climate change impacts on economic growth). EPA (2023) discusses these issues and why they are not ready to be incorporated into the official estimates. • Furthermore, EPA (2023) estimates of the SC-GHG does incorporate climate benefits such as CO2 fertilization and reductions in cold mortality discussed elsewhere in this report, and this should be noted and discussed. • Finally, this section ignores areas of real controversy in the calculation of SC-GHG as it is used by the USG – namely the question of global vs. domestic benefits and the treatment of discounting when valuing benefits to future generations. These controversial issues deserve far more attention in this report instead of spending so much space on issues on the fringe of the literature that are not even included in USG SC-GHG estimates. • EPA (2016) "Technical Support Document: Technical Update of the Social Cost of Carbon for Regulatory Impact Analysis Under Executive Order 12866 Interagency Working Group on Social Cost of Greenhouse Gases, United States Government." https://www.epa.gov/sites/default/files/2016-12/documents/sc_co2_tsd_august_2016.pdf • EPA (2023) "Supplementary Material for the Regulatory Impact Analysis for the Final Rulemaking, 'Standards of Performance for New, Reconstructed, and Modified Sources and Emissions Guidelines for Existing Sources: Oil and Natural Gas Sector Climate Review' – EPA Report on the Social Cost of Greenhouse Gases: Estimates Incorporating Recent Scientific Advances." Docket ID No. EPA-HQ-OAR-2021-0317. https://www.epa.gov/system/files/documents/2023-12/epa_scghg_2023_report_final.pdf • NAS (2017) "Valuing Climate Damages. Updating Estimation of the Social Cost of Carbon Dioxide" https://nap.nationalacademies.org/catalog/24651/valuing-climate-damages-updating-estimation-of-the-social-cost-of The new discussion by the EPA simply rehashes longstanding issues. Switching to separable models like FaIR isn't an advance, because everything still comes down to choice of ECS, discount rate, etc. They add some new damage components but as discussed they jumped on the M17 findings prematurely. Ch 11 focuses a lot on non-SCC topics like the relationship between temperature and growth because that's been the focus of a lot of research. It's not the case that this work is too new to be incorporated into SCC calculations. Moore and Diaz (cited) for example incorporated the Dell et al result into an SCC model. The problem is that the temperature signal in growth isn't robust so economists aren't convinced it belongs in the models. We don't discuss the global vs local benefits issue mainly because standard SCC models have always assumed we should measure global effects and we are not offering an argument otherwise.

DOJ_00000715

11	116-120	Section 11.1	• This chapter has a heavy focus on the relation between climate change and economic growth and how this relationship factors into the SCC. There is an ongoing debate in the literature about persistence in climate damages as measured by changes in economic growth over time; however, these persistence effects on economic growth are not considered in the most recent version of the SC-GHG used by the USG – EPA (2023). This chapter generally ignores the existence of EPA (2023), it is mentioned once in passing, and does not inform readers that these controversial areas of current research are not included in government estimates of the SC-GHG. • EPA (2023) page 58 says, "Given the statistical insignificance of the estimated coefficient on the productivity indicator in the published Howard and Sterner meta-analysis, the SC-GHG estimates presented in this report do not rely on Howard and Sterner's specifications that include productivity effects. This is consistent with the authors' recommendations in the published paper, to only consider the inclusion of the productivity impact in sensitivity analysis. However, the question of whether the effects of climate change impacts (e.g., temperature, tropical cyclones, and other extreme weather events) on the economy are only temporary or persistent is an active area of research. Over the past decade, a host of empirical studies have found evidence of temperature changes having persistent effects on the economy (e.g., Dell et al. 2012; Burke et al. 2015; Moore and Diaz 2015; Deryugina and Hsiang 2017; Ricke et al. 2018; Burke and Tanutama 2019; Colacito et al. 2019; Henseler and Schumacher 2019; Kahn et al. 2021; Kumar and Khanna 2019; Bastien-Olvera et al. 2022); this is an important finding because even small changes in economic growth rates accumulate into large economic impacts over time." Some are discussed in Section 11.1.2 but McKitrick's review is more up to date.
11	116	1	• "Economists have long considered climate a relatively unimportant factor in economic growth, a view echoed by the IPCC itself in AR5." • It would be good to update this to the relevant conclusions in AR6 to reflect the more recent literature. AR6 didn't have an economics chapter comparable to AR5.
11	117	5	• This section makes an important point, much of the public does not understand that climate impacts are relative to projected future without climate change and need to be put in the context of economic growth and a future where our decedents are better off than we are today. O'Neill (2023) is a useful citation here, finding that, "Climate change research and assessments, including the most recent IPCC report, paint an increasingly dire picture of the future. However, the assumption that the future will be worse than the present may be wrong for many aspects of human well-being." • O'Neill, B.C. Envisioning a future with climate change. Nat. Clim. Chang. 13, 874–876 (2023). https://doi.org/10.1038/s41558-023-01784-4 Citation added
11	119	3	• "Overall they could not detect a temperature effect on GDP or GDP growth, and they estimated the 95 percent confidence interval for the impact on global growth as of 2100 even under the exaggerated RCP8.5 warming scenario spans .86 percent to +388 percent. In other words the net effect is likely positive but too uncertain to distinguish from zero." • This finding from Newell et al. (2021) needs to be contextualized with their complementary finding that models excluding growth effects and relating temperatures to GDP levels are far more certain. This is important to include since the actual USG application of SC-GHG does not include growth effects. • Newell et al. (20201) states, "Models relating temperature to GDP levels yield climate impact estimates that are far more certain. The best such models imply GDP losses by 2100 of 1–3%, consistent with damage functions currently embedded in the major integrated assessment models that underpin the U.S. social cost of carbon." The discussion in this section is focused on the effect of dT on growth. The discussion of how dT affects the level of income is what 11.1.1 focuses on. It's very regionally heterogenous so the small global average reported in Newell et al. isn't very insightful.
11	119	6	• "To summarize, economists consider climate a relatively unimportant factor in economic growth, a view echoed by the IPCC itself in the Fifth Assessment Report." • Need to update to reflect AR6 findings. See above

DOJ_00000716

11	121		• "The concepts of estimation and uncertainty do not readily apply to SCC calculations." • The discussion of uncertainty in IAMs should reflect EPA (2023) which incorporated many major advances in the treatment of uncertainty in integrated assessment modeling. See section A.8 of EPA (2023) for a summary of the quantified sources of uncertainty in the SCGHG estimates presented in EPA (2023) • EPA (2023) "Supplementary Material for the Regulatory Impact Analysis for the Final Rulemaking, 'Standards of Performance for New, Reconstructed, and Modified Sources and Emissions Guidelines for Existing Sources: Oil and Natural Gas Sector Climate Review' – EPA Report on the Social Cost of Greenhouse Gases: Estimates Incorporating Recent Scientific Advances." Docket ID No. EPA-HQ-OAR-2021-0317. https://www.epa.gov/system/files/documents/2023-12/epa_scghg_2023_report_final.pdf Our point is that the key underlying parameters are uncertain, and the range of SCC estimates merely reflects those uncertainties. The fact that the EPA proposes ways to compute distributions of the SCC doesn't affect this point, it follows from it.
11	121	3	• "Economists use IAMs to compute the SCC. Two of the best known are the Climate Framework for Uncertainty, Negotiation and Distribution ("FUND", Tol 1997) and Nordhaus' DICE." • This is old literature. Given the advances since FUND and DICE were the leading SCC models, and this report's focus on literature post-2020, this section should be updated to focus on the models used to calculate the SC-GHG in EPA (2023) which represents advances over the approach used in FUND and DICE in response to NAS (2017) recommendations. Added a mention of this. • EPA (2023) "Supplementary Material for the Regulatory Impact Analysis for the Final Rulemaking, 'Standards of Performance for New, Reconstructed, and Modified Sources and Emissions Guidelines for Existing Sources: Oil and Natural Gas Sector Climate Review' – EPA Report on the Social Cost of Greenhouse Gases: Estimates Incorporating Recent Scientific Advances." Docket ID No. EPA-HQ-OAR-2021-0317. https://www.epa.gov/system/files/documents/2023-12/epa_scghg_2023_report_final.pdf
11	121	4	• "and a 'judgmental adjustment' of 0.5 percent for excluded impacts at 3°C warming" • EPA (2023) is the most up to date representation of the USG approach to SC-GHG incorporating the recommendations of the NAS (2017), and EPA (2023) explicitly does not included an adder for missing damages. This is another example of this chapter focusing on older less relevant literature, and it really should be comprehensively updated to address EPA (2023). Barrage and Nordhaus is a (2024) paper. We don't endorse their approach, just describe it. But in some respects the EPA approach is already obsolete because the new Administration has abolished the SCC. • EPA (2023), page 59 states, "the model runs performed for this report do not adopt a 25% adder (as used in the DICE model (e.g., Nordhaus 2017)) to account for unknown or missing damages for the meta-analysis-based damage module." • EPA (2023) "Supplementary Material for the Regulatory Impact Analysis for the Final Rulemaking, 'Standards of Performance for New, Reconstructed, and Modified Sources and Emissions Guidelines for Existing Sources: Oil and Natural Gas Sector Climate Review' – EPA Report on the Social Cost of Greenhouse Gases: Estimates Incorporating Recent Scientific Advances." Docket ID No. EPA-HQ-OAR-2021-0317. • NAS (2017) "Valuing Climate Damages. Updating Estimation of the Social Cost of Carbon Dioxide" https://nap.nationalacademies.org/catalog/24651/valuing-climate-damages-updating-estimation-of-the-social-cost-of

DOJ_00000717

11	122	6	• "Abatement costs: IAMs represent the cost to the economy of reducing CO2 emissions. If CO2 emission reductions are assumed to be inexpensive, then the model will conclude that the optimal policy should aim for deeper emission cuts and vice versa." • IAMs such as DICE are often used in a mode of calculating the optimal level of abatement where they do indeed compare the SCC with the marginal cost of abatement to find the optimum. However, these abatement costs are not part of the SCC calculation, and as used by the USG for the purpose of regulatory impact analyses, this feature of these IAMs is not used. Instead the USG has other more appropriate tools for analyzing the costs of specific regulations. This distinction is important here as the assumptions about the cost of emissions abatement does not have any bearing on the calculation of the SCC. The paragraph has been rewritten to clarify this.
11	122	7	• "For example, in 2023 the U.S. Environmental Protection Agency raised its preferred SCC value about 5-fold over the estimates it had issued ten years earlier. This is not because new data had been collected or better mathematical methods had been invented, but because new assumptions had been used, and the validity of those assumptions was a separate question." • This paragraph contains the only reference to EPA (2023). First, the characterization of this update as only because new assumptions are used is factually incorrect. EPA (2023) represents a significant change to how the USG calculated the SC-GHG moving away from the FUND/DICE/PAGE models used in the IWG era (see EPA (2016)) to a modular approach as recommended by NAS (2017). This chapter needs to address the NAS (2017) recommendations and the EPA (2023) response to those recommendations to capture how SC-GHG was actually used by the USG and how the literature has evolved over time. The tabulations in EPA 2023 p. 81 show that if they had not changed the Ag productivity assumption and added a large mortality cost they'd have ended up with SCC numbers very close to the 2013 IWG numbers. Assuming very low discount rates did the rest. Using the FaIR model with the DSCIM and GIVE damage modules wasn't the key change, it was • EPA (2016) "Technical Support Document: Technical Update of the Social Cost of Carbon for Regulatory Impact Analysis Under Executive Order 12866 Interagency Working Group on Social Cost of Greenhouse Gases, United States Government." https://www.epa.gov/sites/default/files/2016-12/documents/sc_co2_tsd_august_2016.pdf • EPA (2023) "Supplementary Material for the Regulatory Impact Analysis for the Final Rulemaking, 'Standards of Performance for New, Reconstructed, and Modified Sources and Emissions Guidelines for Existing Sources: Oil and Natural Gas Sector Climate Review' – EPA Report on the Social Cost of Greenhouse Gases: Estimates Incorporating Recent Scientific Advances." Docket ID No. EPA-HQ-OAR-2021-0317. https://www.epa.gov/system/files/documents/2023-12/epa_scghg_2023_report_final.pdf § NAS (2017) "Valuing Climate Damages. Updating Estimation of the Social Cost of Carbon Dioxide" https://nap.nationalacademies.org/catalog/24651/valuing-climate-damages-updating-estimation-of-the-social-cost-of
11	123	2	• "It should also be noted that the SCC is focused on the social costs of CO2 emissions from fossil fuel use. It does not measure the private marginal benefits to consumers and society from the availability of fossil fuels. Public willingness to pay for fuels of all types indicates the value to society of reliable, abundant fossil energy." • Two points to make about this section. First, the benefits to society generally accrue from the provision of energy services, not from specific fuels." A distinction without a difference in this context. Second, the private marginal benefit of the availability of fossil fuels or energy services is not part of the SCC because changes in the cost and provision of the energy services should be part of the other side of the cost benefit analysis. The SCC is used to characterize the benefits of GHG emissions abatement, and the changes in the costs and availability of energy services are part of the cost of emissions abatement. Agreed, changed the wording to clarify
11	125	5	• "the uncertainty of SCC estimates doesn't mean that other regulatory measures are inherently better or more efficient." • 'regulatory measures' is a poor word choice here as it can be confused with the regulation itself instead of the metric used to assess the regulation. Changed measures to instruments

DOJ_00000718

11	123-125	Section 11.1	• Section 11.2.4 has an interesting discussion of tipping points. This is an active area of research in the field, however it needs to be noted that tipping points or tipping elements are not included in the SC-GHG as used by the USG, see EPA (2023). • EPA (2023), page 3 says, "For example, the modeling in this report omits most of the consequences of changes in precipitation, damages from extreme weather events, the potential for nongradual damages from passing critical thresholds (e.g., tipping elements) in natural or socioeconomic systems, and nonclimate mediated effects of GHG emissions other than CO2 fertilization (e.g., ocean acidification due to CO2 emissions, tropospheric ozone formation due to CH4 emissions). Importantly, this update does not yet reflect interaction effects and feedback effects within, and across, natural and human systems. For example, it does not explicitly reflect potential interactions among damage categories, such as those stemming from the interdependencies of energy, water, and land use. These interactions and feedbacks, and others, were highlighted by the National Academies as an important area of future research for longer-term enhancements in the SC-GHG estimation framework." Not necessary to say this since EPA is on hold from doing SCC calculations
12	129	1	• This chapter summary is misleading as it is describing change from today's temperature rather than the effect on future temperatures. A change from today's temperature is the future temperature. Not sure what the objection is.
12	129	2	• "And even if global emissions were to stop tomorrow, it would take decades or centuries to see a meaningful reduction in the global CO2 concentration and hence human influences on the climate." • If global emissions were to go to zero tomorrow, CO2 concentrations would stabilize, and global temperature would be approximately constant. Net negative CO2 would result in reductions of concentrations and temperatures. In other words, while reducing global CO2 emissions to zero might not lead to near-term reductions in CO2 concentrations from today's levels, it would stop future increases in CO2 concentrations. Consistent with what we stated.
12	129	3	• This section is focused on unilateral action, but needs to address questions related to collective action and individual actions by multiple parties when the benefits of abatement and the damages from emissions have extensive externalities. • Kotchen (2021) provides a theoretical perspective on the global vs. domestic SCC question and addresses questions related to how an individual country's decisions are impacted by the expected choices of other countries given that GHG emissions are globally mixed the benefits of GHG abatement are shared widely. • Kotchen (2021). Which Social Cost of Carbon? A Theoretical Perspective. Journal of the Association of Environmental and Resource Economists. https://doi.org/10.1086/697241 An interesting line of thought but we can't get into game theoretic models here.
12	129	4	• "Since that rate has been averaging about 50 percent of emissions in recent decades, a reduction of global emissions by 50 percent would (at least temporarily) halt the rise in atmospheric CO2." • This may be addressed in earlier chapters that this reviewer has not read yet, but the standard framing is that stabilizing CO2 concentrations requires balancing emissions by sources and removals by sinks. Removals by sinks includes both natural sequestration and anthropogenic sequestration (e.g. afforestation if it can be done that increases the overall land sink removal, or direct air capture). It could be useful to clarify this here. The discussion is only an approximation for illustrative purposes
12	129	5	• "Lomborg (2016) estimated that full compliance with the Paris Accord would not stop warming, it would only prevent about 0.1C warming and delay hitting the baseline year 2100 temperature levels by about a decade." • Note that the Lomborg (2016) finding is related to, "the of impact of the total, global emission cuts implied by all the submitted INDCs," this is different than 'full compliance with the Paris Accord' as the INDCs analyzed in the paper are only the first round of Intended Nationally Determined Contributions submitted ahead of COP-21, and the Paris Accord requires additional Nationally Determined Contributions every 5 years. Since Lomborg (2016) only analyzes these INDCs, and parties have submitted two rounds of NDCs since then, suggest changing the wording here to, "… full compliance with initial commitments submitted ahead of the Paris Accord." Changed.

DOJ_00000719

12	129	Chapter	• [NOTE: this comment is long and could be difficult to read in excel. It is included here once as a full comment, then again broken into multiple parts for ease of reading. This is PART 1] • Section 12.1 is titled, "The scale of the problem," is framed around contrasting criteria air contaminants with CO2 emissions; however, there really are three separate issues that need to be disentangled: Stock vs. Flow. • The challenge here is that abatement costs borne by people today benefit people in the future – temporal externalities. • CO2 emissions are a stock pollutant, so impacts depend on the cumulative emissions to date, whereas traditional criteria are a flow pollutant and impacts depend on the emissions at that point in time. Emissions of a stock pollutant going to zero will not affect impacts at that point in time, as the stock remains unchanged, but will have large impacts in the future as the stock will cease to increase until emissions resume; whereas emissions of a flow pollutant going to zero will immediately eliminate impacts, but impacts will have no lasting effects on future impacts as they will immediately resume when emissions resume. • The sentence at the end of the second paragraph of this section reads, "And even if global emissions were to stop tomorrow, it would take decades or centuries to see a meaningful reduction in the global CO2 concentration and hence human influences on the climate." This is conflating the expectations of how stock and flow pollutants work – if global emissions were to stop tomorrow, the fact that there would be no meaningful reduction in global CO2 concentrations is simply the nature of how stock pollutants work, but there would be very large impacts on future temperatures since the stock would cease to increase. Conflating isn't the right word. We are pointing out the stock-flow issue. • The stock nature of CO2 emissions is a real challenge for justifying CO2 emissions reductions, but it is centered on justifying the costs of abatement being born by people today in order to create a stream of benefits that grow over time and primarily accrue to future generations. This leads to questions important questions about how decision-makers should think about inter-generational discounting, and what costs should or should not be borne today for the benefit of future generations that will potentially be substantially better off. Dealt with in the IAMs section • It's worth noting that since CH4 emissions are relatively short lived, they behave much more like a flow pollutant than a stock pollutant. If CH4 emissions went to zero, concentrations would fall relatively quickly, and the temperature effects would happen on a much shorter timescale, but if CH4 emissions fully resumed, concentrations would return to previous levels there would be no lasting impact of the previous reductions. This is to point out that the stock vs. flow distinction also happens between different greenhouse gasses and is not purely a distinction between GHG emission and criteria pollutants. The CH4 case is interesting and we haven't looked at it. Also natural sources and sinks are complicated for CH4
12	129	Chapter	• [NOTE: this comment is long and could be difficult to read in excel. It is included here once as a full comment, then again broken into multiple parts for ease of reading. This is PART 2] Globally mixed. • The challenge here is that abatement costs borne by people in one location benefit people in other locations – spatial externalities. • The next issue is that GHG emissions are globally mixed, so that emissions in any one location have impacts all over the world. This is a distinct issue from the stock vs. flow issue, as the CH4 example above showed a flow pollutant can also be globally mixed. One can also consider a stock pollutant that is not globally mixed, such as groundwater pollution that depends on the stock of contaminants accumulating in the groundwater not just the flow in any one time period as one would see in surface water pollution. • The globally mixed nature of GHG emissions is a real problem for justifying climate policy as the benefits of any one country's actions primarily accrue to people in other countries. Conversely, a country benefits from the actions of every other country, not just their own actions. This is a problem of game theory and collective action, as unilateral action may not be justified even if collective action would be. It's worth noting that this isn't just a problem of scale – these same problems arise for globally

DOJ_00000720

			mixed CH4 emissions even though as noted above they behave more as a flow pollutant, and would arise for any globally mixed pollutant regardless of the scale of the problem. There is an extensive literature on transboundary pollution that explores these issues. Agree with all this, but discussing these points wouldn't change our overall conclusions
12	129	Chapter	• [NOTE: this comment is long and could be difficult to read in excel. It is included here once as a full comment, then again broken into multiple parts for ease of reading. This is PART 3] Scale. • The challenge here is that solving the problem requires enormous change and potentially enormous costs. However, individual actions need to be considered at the margin. • As discussed in this section and the comments above, stabilizing CO2 concentrations and stopping the increase in global mean temperature requires balancing anthropogenic emissions and removals by sinks. The level global mean temperature stabilizes at would generally depend on the cumulative CO2 emissions up to the point CO2 emissions on net go to zero (the stock of CO2 emissions), and the level of short-lived non-CO2 emissions at that time (the flow of non-CO2 emissions). This would involve an enormous change to the global energy system. The costs of this change would be highly dependent on the timing of reaching net-zero CO2 emissions – in 10 years by 2035 would involve crippling costs to the global economy, in 100 years by 2125 would involve a far more gradual transition and likely impose minimal costs when discounted back to today. • What is missing in this chapter is an acknowledgement that policy needs to be thought of at the margin. Do the marginal benefits of the policy equal or exceed the marginal costs? This is how economists think of these problems and the essence of how the government conducts cost-benefit analysis to inform decision-makers under E.O. 12866. The case study presented in section 12.2 poses the wrong two question. Showing that a policy's emissions reductions are small relative to global emissions, and the resulting impact on global temperatures is also small is tautological. No individual policy will solve climate change, but that does not mean that the individual policy is not justified. The relevant questions for decision makers are: (1) what is the cost of the marginal ton of emissions reductions by this policy? and (2) are those marginal costs smaller than the marginal benefit of a ton of emissions reductions? In practice, question (2) is very difficult to answer, and requires judgements about how to value benefits to Americans vs. benefits to the rest of the world, how to discount benefits that accrue to future generations, and how to consider the impacts U.S. actions have on the likelihood that other countries will take actions that benefit the U.S. These are difficult questions that need to be answered to justify climate policy, and this section would be improved by acknowledging that these are the questions that need to be addressed instead of the awkward argument that the problem is big, and individual policies are small therefore they can't be justified. Ch 12 is only focused on the scale problem. The reviewer is correct that even if the effects are small that doesn't mean they shouldn't be undertaken. Ch 11 is where the logic of cost-benefit analysis including marginal considerations is explored.

DOJ_00000721

12	129	Chapter	• [NOTE: this comment is long and could be difficult to read in excel. It is included here once as a full comment, then again broken into multiple parts for ease of reading. This is the full comment] • Section 12.1 is titled, "The scale of the problem," is framed around contrasting criteria air contaminants with CO2 emissions; however, there really are three separate issues that need to be disentangled: § Stock vs. Flow. • The challenge here is that abatement costs borne by people today benefit people in the future – temporal externalities. • CO2 emissions are a stock pollutant, so impacts depend on the cumulative emissions to date, whereas traditional criteria are a flow pollutant and impacts depend on the emissions at that point in time. Emissions of a stock pollutant going to zero will not affect impacts at that point in time, as the stock remains unchanged, but will have large impacts in the future as the stock will cease to increase until emissions resume; whereas emissions of a flow pollutant going to zero will immediately eliminate impacts, but impacts will have no lasting effects on future impacts as they will immediately resume when emissions resume. • The sentence at the end of the second paragraph of this section reads, "And even if global emissions were to stop tomorrow, it would take decades or centuries to see a meaningful reduction in the global CO2 concentration and hence human influences on the climate." This is conflating the expectations of how stock and flow pollutants work – if global emissions were to stop tomorrow, the fact that there would be no meaningful reduction in global CO2 concentrations is simply the nature of how stock pollutants work, but there would be very large impacts on future temperatures since the stock would cease to increase. • The stock nature of CO2 emissions is a real challenge for justifying CO2 emissions reductions, but it is centered on justifying the costs of abatement being born by people today in order to create a stream of benefits that grow over time and primarily accrue to future generations. This leads to questions important questions about how decision-makers should think about inter-generational discounting, and what costs should or should not be borne today for the benefit of future generations that will potentially be substantially better off. • It's worth noting that since CH4 emissions are relatively short lived, they behave much more like a flow pollutant than a stock pollutant. If CH4 emissions went to zero, concentrations would fall relatively quickly, and the temperature effects would happen on a much shorter timescale, but if CH4 emissions fully resumed, concentrations would return to previous levels there would be no lasting impact of the previous reductions. This is to point out that the stock vs. flow distinction also happens between different greenhouse gasses and is not purely a distinction between GHG emission and criteria pollutants. § Globally mixed. • The challenge here is that abatement costs borne by people in one location benefit people in other locations – spatial externalities. • The next issue is that GHG emissions are globally mixed, so that emissions in any one location have impacts all over the world. This is a distinct issue from the stock vs. flow issue, as the CH4 example above showed a flow pollutant can also be globally mixed. One can also consider a stock pollutant that is not globally mixed, such as groundwater pollution that depends on the stock of contaminants accumulating in the groundwater not just the flow in any one time period as one would see in surface water pollution. • The globally mixed nature of GHG emissions is a real problem for justifying climate policy as the benefits of any one country's actions primarily accrue to people in other countries. Conversely, a country benefits from the actions of every other country, not just their own actions. This is a problem of game theory and collective action, as unilateral action may not be justified even if collective action would be. It's worth noting that this isn't just a problem of scale – these same problems arise for globally mixed CH4 emissions even though as noted above they behave more as a flow pollutant, and would arise for any globally mixed pollutant regardless of the scale of the problem. There is an extensive literature on transboundary pollution that explores these issues. § Scale. • The challenge here is that solving the problem requires enormous change and potentially enormous costs. However, individual actions need to be considered at the margin. • As discussed in this section and the comments above, stabilizing CO2 concentrations and stopping the increase in global mean temperature requires balancing

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			anthropogenic emissions and removals by sinks. The level global mean temperature stabilizes at would generally depend on the cumulative CO2 emissions up to the point CO2 emissions on net go to zero (the stock of CO2 emissions), and the level of short-lived non-CO2 emissions at that time (the flow of non-CO2 emissions). This would involve an enormous change to the global energy system. The costs of this change would be highly dependent on the timing of reaching net-zero CO2 emissions – in 10 years by 2035 would involve crippling costs to the global economy, in 100 years by 2125 would involve a far more gradual transition and likely impose minimal costs when discounted back to today. • What is missing in this chapter is an acknowledgement that policy needs to be thought of at the margin. Do the marginal benefits of the policy equal or exceed the marginal costs? This is how economists think of these problems and the essence of how the government conducts cost-benefit analysis to inform decision-makers under E.O. 12866. The case study presented in section 12.2 poses the wrong two question. Showing that a policy's emissions reductions are small relative to global emissions, and the resulting impact on global temperatures is also small is tautological. No individual policy will solve climate change, but that does not mean that the individual policy is not justified. The relevant questions for decision makers are: (1) what is the cost of the marginal ton of emissions reductions by this policy? and (2) are those marginal costs smaller than the marginal benefit of a ton of emissions reductions? In practice, question (2) is very difficult to answer, and requires judgements about how to value benefits to Americans vs. benefits to the rest of the world, how to discount benefits that accrue to future generations, and how to consider the impacts U.S. actions have on the likelihood that other countries will take actions that benefit the U.S. These are difficult questions that need to be answered to justify climate policy, and this section would be improved by acknowledging that these are the questions that need to be addressed instead of the awkward argument that the problem is big, and individual policies are small therefore they can't be justified. If the discussion becomes marginal costs/benefit calculations, then at least the non-existential nature of the discussion has been acknowledged, and it reduces to considering mitigation among many other societal priorities. However, valid this line of reasoning, we consider it outside of our remit and prefer to let readers draw their own conclusions.

DOJ_00000723

Ch	page	Para	Comment or Suggested Edit
2	5	Fig 2.2	The graph is not relevant to the discussion. It should only, at most, cover the time period since the last glacial maximum, which occurred ~20 kyr BCE, and common practice is to concentrate on the last 1000 years. Figure 2.2 has been deleted
3	11,12	Sec 3.1.1	There is no quantification of the effects of TSI and volcanic aerosols that would lead to modifications of the radiative forcing shown in the figures In Chapter 6 we discuss ranges of TSI forcing that even the IPCC acknowledges.
3	21,22	Sec 3.3	Many of the arguments and references are dated. Further, the challenge posed is to prove a negative, i.e. that the record used by AR6 is not biased by urban heat island effects. On the contrary, while verbally stating uncertainty, the authors cannot make a claim that the AR6 statement is false. Even if one were to the accept the Soon, et al value of 0.89 deg C/century, the focus on the land surface warming completely neglects the contribution of the oceans to global surface temperature change, which must be considered in any discussion of surface temperature change. The underlying studies frame statistical tests appropriately to test for the presence or absence of an effect. Yes ,the literature is dated and the topic needs renewed attention. The question is bias in the land record, but no one is arguing all surface warming is due to urbanization.
4	30	Sec 4.4	The statement "TCR is more generally related to peak warming and better constrained by historical warming, than ECS." requires further context. While true that the "peak warming" rate achieves a maximum around 70 years, temperature increases continue for several centuries and approaches the ECS value asymptotically. Further, the Lewis (2023) arguments were placed in context by Sherwood and Forest (2024), that identified multiple recent ECS studies that showed, collectively, that the PDF in their original Sherwood, et al paper could not be narrowed. Additionally, the reference to Sherwood et al (2020) is incorrect. It omits many authors and the authors that are listed are not in the correct order. Reference to peak warming deleted.
5	37, 38	Sec 5.4	The analysis presented of the IPCC AR5 figure, Fig 5.6 in the current document, is outdated and should be removed. The issue IS addressed in the AR6, but not graphically, in the text reproduced by the authors. If the section is retained, it should be moved ahead of Section 5.3 to present the material in the correct order chronologically. The analysis in Fig. 5.6 matches the updated data in Fig 5.7, and it is relevant to show that the information was included in the AR5 but only in a figure in the Supplement. The order of presentation in the chapter is appropriate.
6	57	para 1	The conclusion "The rise in Tmin has been strongly related to the growing presence of manufactured surfaces around the weather stations over the last 100+ years (the so-called urban heat island effect; Section 3.3 and Spencer et al. 2025)." is only found in an author's self-citation of Spencer, et al, (2025) that does not appear in the references at the end of Chapter 6. Further, the trend of greater increases in Tmin relative to Tmax is documented and explained in Easterling, et al (1997). https://doi.org/10.1126/science.277.5324.364; Thorne, et al (2016) https://doi.org/10.1002/2015JD024584. The trend cannot be attributed to UHI effects. We added citations to the literature to substantiate the point.
8	85	para 5	"… datasets with high TSI variability can explain more than 70 percent of the temperature variability since preindustrial times." Variability on what time scales? 11-year cycles? How would this impact the well documented surface temperature increase of > 1 deg C global temperature change since 1900?

			There is a whole spectrum of variability in TSI beyond the 11-year cycle. These are discussed in the papers we reference.
8	85,86,87	"Natural variability of large-scale ocean circulations"	The discussion neglects the influence of vertical mixing on surface temperature. The global ocean has warmed, as documented by increases in global ocean heat content, e.g. Murphy, et al (2009) doi:10.1029/2009JD012105 We do not understand the comment.
8	88,89	Optimal fingerprinting discussion	This section is hardly a balanced and objective review. The report authors are known opponents of optimal fingerprint approaches and have been a loud, but very small minority voice. It is interesting that even they conclude "...these analyses do not falsify results of the IPCC optimal fingerprinting method..." The point is that falsification would require redoing all the underlying studies. The findings however show that the method is flawed and the justification for relying on it is invalid.
8	90,91,92	Section 8.4	This discussion is incomplete and fails to take into account the extensive literature on cloud and surface albedo feedbacks.. There is an extensive discussion about the post 2015 period and recent record annual global surface temperatures, implying, but not stating, that recent changes are the result of natural variability, or decreases in atmospheric aerosol concentrations. Comparing the radiative forcing from these changes with long-term GHG forcing, particularly CO2 is misleading to the average reader. If the reduction in albedo can be tied to atmospheric cloud and aerosol changes, as the authors state, they cannot ignore the liklihood that the changes are the result of anthrogenic factors, i.e. sulfate aerosol reduction through cleaner technology and the well-documented positive low-cloud feedback. The discussion is incomplete because the underlying science is incomplete, as we emphasize. We are surveying a complex area of ongoing research without taking a strong position ourselves.

DOJ_00000725

Full document			In the limited time allowed, this reviewer concentrated on sections related to the physical climate and climate change. Frankly, the document was discouraging. Secretary Wright wants a " ... a more thoughtful and science-based conversation about climate change and energy." I find that this report distorts the science in much the same way as the media coverage about which he complains. Most notable are the omissions or under-reported significant climate changes, such as sea-ice decline, changes in the global water cycle and increases in heat-stress due to increases in absolute humidity (from water-vapor feedback). Further, the examples used by the report authors are narrow and appear to be selected to emphasize uncertainty, while the more rigorously evaluated science that contradicts their limited discussion is ignored, perhaps because it does not fit their narrative.This is unfortunate, because I believe it detracts from the much needed discussion about the future, includiing energy policies, technologies and trade-offs. I encourage DOE to start the discusion by accepting the well-reviewed and broadly accepted scientific conclusions of the IPCC Working Group 1, with respect to the observations and analyses of climate change in the 20th and 21st centuries. Skepticism regarding predictions/projections of future climate based on posited scenarios is justified. As a member of the physical climate research community, I believe their are better uses for the models (and the computer resources they consume) than scenario projection simulations, to inform the discussion that is urgently needed about the future. Comments noted.

DOJ_00000726

Chapter Number	pg	para	Comment or Suggested Edit
Foreword	vii	4	The stated charge to the team was to summarize the current state of climate science, but in the Preface the team states that it chose to focus on topics that are downplayed in or absent from current assessment reports. To accurately describe the contents of the report, the Foreword should also state that the report is a summary of the things that the author team thinks have been downplayed in major climate assessment reports. Noted, the Preface has been modified. Our charge was not to summarize the whole of climate science.
Foreword	vii	8	The statement about climate change not being the greatest threat facing humanity is a value judgement. Since the Secretary criticizes others for blurring the line between scientific conclusions and policy recommendations in the second, fourth, and sixth paragraphs of this Foreward, it is hypocritical to offer a value judgement without clearly labeling it as such and noting that such conclusions must necessarily involve one's beliefs in addition to scientific information. We did not write the Secretary's foreword.
Exec Summ	viii	2	It is misleading (cherry picking) to only mention "global greening" (i.e., the influence of elevated CO2 on plant growth) here without also noting the impacts of elevated temperatures and changing precipitation patterns on ecosystem health and agricultural productivity. (This comment is also true of the underlying content on pages 3-7) This issue has been addressed with wording changes to acknowledge the other contributors.
Exec Summ	viii	2	It is misleading to state that ocean pH levels are within the range of natural variability. This statement is not true on the timescales governing the impacts of ocean acidification on ocean ecosystems and fisheries. (This comment is also true of the underlying content on pages 8-9) The statement has been removed.
Exec Summ	viii	3	It is inaccurate to say that "scenarios of CO2 emissions have tended to overestimate observed levels". As the authors themselves note on page 15, it is impossible to reliably predict societal behavior regarding energy production and other sources of emissions, so the climate science community has never provided or suggested that there is a single predictive scenario against which future emissions could be judged. Rather, there has always been a range of projected emissions scenarios, and emissions have always tracked wtihin the envelope of those scenarios. The authors make a reasonable point in the full text about the large number of climate studies that have used RCP 8.5, whereas actual emissions have recently been closer to RCP 4.5. This would be a more appropriate finding to include here in the executive summary. The point being made here is that observations have tracked the low end of the envelopes, a problem going back decades. See Figure 3.2.1
Exec Summ	viii	4	Stating that climate models "offer little guidance on how the climate responds to elevated CO2" is at best an unjustified (and at worst a biased) judgement given that the authors chose to focus only on the shortcoming and deficiencies of these models, and do not account for the progress made in improving the ability of these models to reproduce many key aspects of observed climate change. The same is true for all of Chapter 5. It is informative for readers to see key ways in which models fail to match observations especially those most relevant for policy making. The continuing broad range of responses is an important limitation to their fitness for purpose.

Exec Summ	viii	5	Stating that climate models "generally run hot" is an inaccurate and misleading summary statement. A large number of papers and scientific assessments have validated the ability of climate models to accurately simulate many major aspects of global climate. Like all models, climate models are imperfect, and some models have recently shown a tendency to produce higher climate sensitivities--the IPCC AR6 acknowledged this "hot model problem" and there has been considerable discussion in the scientific literature about it and its implications for impacts studies. But this is a relatively recent phenomenon, and there could be other reasons for the recent mismatch (i.e., under-estimates of the reduction in aerosol cooling due to air pollution controls). A balanced scientific assessment would also note, for example, that climate model projections from the 1970s and 80s have accurately predicting the observed trend in global temperature over the past few decades. The question is not whether the models “accurately simulate many major aspects of global climate”. It is rather whether the models accurately simulate the climate’s response to anthropogenic influences, which is quite a different matter. Our statements are substantiated by the Figures in Ch 5 (especially Figs 5.2 - 5.4). As we discuss, the problem of the tropospheric mismatch goes back decades.
Exec Summ	viii	6	It is misleading and inaccurate to say that most extreme weather events do not show long terms trends. It is true that some kinds of extreme events, like tornadoes, have not shown appreciable or detectable changes, and that changes in wildfire must account for changes in land management. But a "summary of the current state ofthe science" should acknowledge that there is clear evidence that heat waves are becoming more frequent and more extreme, extreme precipitation and nuisance flooding are becoming more common, etc. (This comment is also true of the underlying content in Part II) The chapter presents a great deal of data that substantiates our summary statement. We also provide clear indications on heatwave trends including where they are increasing in frequency. Our assessments match those in the IPCC and NCA documents.
Exec Summ	viii	6	It is misleading to state that the aggregate sea-level rise trend in U.S. tide gauges is not accelerating, because as noted in the same sentence, there are significant regional differences in SLR (primarily due to differences in land subsidence), so only looking at domestic gague data is insufficient to determine if sea-level rise--an inherently global process--is accelerating, with regional factors superimposed on that global trend. There is clear evidence that global sea level rise is accelerating. Moreover, while land subsidence has offset sea level rise in some U.S. regions, the opposite is true in others, and in those reasons the combined effects of sea level rise and subsidence are posing considerable risks to people and infrastructure in those regions...but this important context is omitted. (The same is true of the sea level rise analysis on pages 75-78.) We state that global sea level rise has accelerated in recent decades. The reviewer needs to provide evidence for the claim of acceleration. SLR is a regionally-heterogeneous phenomenon and we discuss the differences by location. We present tide-gauge data for many locations so readers can see the situation for themselves.

DOJ_00000728

Exec Summ	viii	9	Most of the sentences in this paragraph are not factual in nature. For example, the call for uninterrupted observations of the global climate system is a research recommendaiton that is outside the remit of this report and is not supported by text within the document. The same sentence also implies that current emissions scenarios are not "realistic", which is not a defensible statement given that historical emissions have tracked within the envelope of previous emission projections (see comment above and Figure 3.2.2), and argues that climate models should address biases and uncertainties, which is something that every climate modeling team already spends an enourmous amount of time doing. If retained, the non-scientific portions of this paragraph should be moved to the Preface, and the misleading statements should be corrected. The paragraph has been moved to the end of Chapter 12. See above regarding emission scenarios.
Preface	ix	1	The focus on "whether carbon dioxide emissions engdanger the U.S. public" is slightly different from the stated focus in the Foreward on "the Nation's climate". This distinction is important because climate change and its impacts outside of U.S. borders can endanger the U.S. public both directly (e.g., global processes affecting sea level rise in the United States, or the impacts of climate change on overseas military installations) and indirectly (i.e., impacts of climate change on international agricultural production and trade dynamics). The reference to endangerment has been removed.
2	3	1	The two summary statements provide an extremely narrow and misleading view of "direct impacts of CO2 on the environment" (the chapter title). The most obvious direct impact of CO2, in the context of climate change, is its role in global radiative forcing, which is covered in the next chapter but not mentioned here. The chapter should at a minimum be retitled, but better yet combined with the following chapter which discusses other aspects of increasing CO2. The effect of CO2 on the climate takes up the bulk of the report.
2	3	2	It is misleading to state that ocean pH levels are within the range of natural variability. This statement is not true on the timescales governing the impacts of ocean acidification on ocean ecosystems, fisheries, and other processes. The evidence we cite shows that pH levels are in the range of natural variability. Whether the rate of change is, is much more difficult to establish because of the limitations of paleo records. Also the spatial heterogeneity is not subject to comprehensive measurement, which precludes straightforward assessment.
2	5	1	It is misleading to show (only) a graph of CO2 levels over hundreds of millions of years. These timescales are generally not relevant to processes and issues surrounding anthropogenic CO2 increases. For example the authors in multiple places make statements about CO2 levels during the last glacial maximum, but those fluctuations are indetectable on a graph with such a long timescale. The figure has been removed.
2	8	1	Acidification is not a misnomer…the word literally means to make something more acidic, which is what is happening. The authors may choose to argue that the term is misleading since the oceans are slightly basic, but that is not the same thing as a misnomer. We consider it a misnomer for the reasons stated. The oceans are not becoming acidic.

DOJ_00000729

2	8	1	It is misleading and largely irrelevant to discuss ocean pH levels tens of thousands or millions of years ago, because that timescale is not relevant to the impacts associated with anthropogentic ocean acidification on ocean life. It is well documented that recent changes in ocean pH are happening ~100 times faster than natural fluctuations prior to human CO2 emissions, and marine species must adapt to changes in conditions on timescales of a few of their lifetimes, which is clearly not millions of years. The reviewer needs to provide specific sources for these statements. Also, it is a relevant point to make if current marine life evolved under conditions of much lower pH.
2	9	4	Similar to previous comment--changes in marine life over hundreds of millions of year has little relevance to the survival of marine species on decadal timecales due to anthropogenic ocean acidification. Are the authors trying to suggest that U.S. society would be well served by going back to conditions during the Jurassic? See earlier response.
3	13	2	The IPCC probably discounted the results reported in Connolly (2021) because that study included methodological errors that were documented in sevearl subsequenty publictions, which the authors do not acknowledge. A serious assessemnt of TSI would not cherry-pick a single study, especially one that has been shown to include serious erros. The reviewer is probably referring to a comment by Richardson and Benestad, but Connolly et al. replied effectively to their critique.
3	14	4	It is unclear what the authors mean by "other natural sources of energy imbalance". If the authors are aware of a plausible additional source of energy imbalance they should state what it is rather than making vague statements without providing any evidence that such sources might exist. Surely the reviewer acknowledges that there are unknowns in the climate system
3	14	5	This is one of several places where the authors discuss the CO2 levels at which C3 plants begin dying in the context of the last glacial maximum. This is misleading, because there is no evidence that CO2 levels would have continued falling below the levels of the last glacial maximum, and irrelevant to the stated focus of this report, because they rebounded to 280 ppm many centuries before human activities began producing large amounts of CO2. The reviewer needs to provide evidence for the assertion that CO2 levels would not have continued falling.
3	15	1	The oceans and land surface absorb more like 60% of CO2 emissions. The 50% figure is repeated multiple times in the ensuing pages and should be corrected. We are unfamiliar with the 60% number; the sources with which we are familiar generally report numbers closer to 50%. The reviewer has not cited any sources for his or her statement.
3	20	2	The final sentence on this page is misleading and confusing as written. Most studies of the land carbon sink suggest that the rate at which it is increasing is declining, and several studies suggest that the ocean sink is declining. The authors should also explain the relevance of their statements here, because it isn't clear. Our statement is consistent with the sources we cite. Unfortunately the reviewer did not provide references.
4	26	6	The inclusion of a paragraph with high-level summary statements about climate policy here is confusing and inappropriate. This content belongs in chapter 11. We only make a brief introductory statement and otherwise defer the discussion to Ch 11.

DOJ_00000730

4	29	1	The point about observed global temperature trends being consistent with both high-ECS high-aerosol and low-ECS low-aerosol worlds is an important one. It would be good to acknowledge that uncertainty in ECS is not just due to uncertainties in climate models, but also the lack of accurate measurements of pre-industrial aerosols and thus anthropogenic changes in aerosol forcing. And this uncertainty cuts both ways--if we live in a high-ECS world that has been "masked" by strong aerosol cooling, reducing air pollution could result in rapid warming (and this may be linked ot the "hot model" problem as well). Agreed
4	29	2	The point about ECS values derived from past climate states (especially cooler ones) possibly not being totally representitive of the current climate is another good point, one that would be good to acknowledge in their ealrier and later discussions about uncertainty and the rationales for emissions reducitons (e.g., on page 26 and in Chapter 11). Agreed.
4	30	1	The relatively shallow treatment on TCR relative to ECR here is puzzling, since the authors acknowledge that it is better constrained, and it is also a more relevant value for projected warming over the next several decades. The first sentence here also describes it as an observational constraint, but it is not, it is a metric that can be produced from either data or models (or both), and climate models are routinely used to run TCR experiments. ECS is more widely-used than TCR which is why we focus more attention on it.
5	32	1	A more accurate title of this chapter would be "deficiencies in climate models" because the authors focus almost exclusively on processes and features that models have struggled to reproduce, rather than a balanced assessment that also indicates what these models do well. We changed the title to take this into account.
5	34	1	Scaffeta (2023) has been widely criticized in the scientific literature for its methods and conclusions. These results should not be presented without acknowledging these concerns, or better yet, the authors should attempt to survey the literature on this topic rather than presenting results from a single controversial paper. The reviewer is referring to an exchange regarding a different paper. We are unaware of any published critiques of the Scafetta paper we cite.
5	34	2	Spencer (2024) is not a peer reviewed journal paper and is not really appropriate to include here when there are many papers on this topic that have been peer reviewed. The reviewer should have provided references. We are unaware of any peer reviewed papers that present the comparison we show. We provide traceable accounts for the underlying data, all of which is from official sources.
5	35	1	The statement that the signal for anthropogenic greenhouse warming emerges first and most strongly is not supported and is inconsistent with my understanding of climate dynamics. The following sentence is also dubious (and probably backwards) since models run with observed surface temperatures tend to produce much better mid-tropospheric temperature simulations. The statement about early and strong emergence of the CO2 signal in the tropical troposphere is in the IPCC TAR and subsequent reports. Even models constrained with observed sea surface temperatures produce excess amplification aloft.

DOJ_00000731

5	36	1	In most places the authors correctly describe the discrepancy between models and observations as a mismatch, which is appropriate because observations of mid-tropospheric temperatures are also subject to uncertainty (as indicated in the error bars in Figure 5.4). This is one of the reasons for the IPCC confidence assessment noted in the following paragraphs. However, here and in a few other places in this section the writing implies that differences can be solely attributed to model deficiencies. We don't take a position on the ultimate cause however we do note that the biases are pervasive across models and multiple observational data sets.
5	37	1	This section should be combined with the previous one as it is really just elaborating on the same discrepancy between climate models and observational estimates of tropospheric tempeartures. One section discusses the discrepancy of trends and the other discusses the discrepancy of amplification rates, which is why the sections are separate.
5	39	1	There has indeed been considerable controversy about this particular metric. It is curious that the authors choose to cite two older papers here (2008 and 2009) rather than the rich recent literature, especially since they went to the trouble of updating on of their graphics with 2024 data. Recommend including a more balanced assessment of this discrepancy, it's potential causes, and recent efforts to address it, as well as noting that climate models are able to accurately capture many other aspects of climate change. Again, it is unfortunate that the reviewer did not provide any citations to this rich recent literature. We cited the key papers we are aware of.
5	39	1	This entire section is very misleading as it cherry-picks a specific result and takes it out of important context. The reason why stratospheric cooling has slowed (and, at least in one study, even warmed) in the past two decades is due to the recovery of the ozone layer. This is clearly stated in the Philipona et al article cited by the authors and in the IPCC report. Additionally, satellite-based estimates of stratospheric temperature (which is data the authors highlight in the previous section) do not show the same trends. This section should be removed or amended to note that stratospheric temperatures are influenced by multiple factors and that a comprehensive analysis of stratospheric temprature trends is fully consistent with those projected under climate warming scenarios. We have added a sentence discussing the ozone recovery issue and make reference to the recent Santer et al. study.
5	41	1	Many observational studies have shown that snow cover is decreasing, and have explained why it is more meaningful and useful to look at spring trends in snow cover, as well as why observations of snow cover can be uncertain. The issue here is model projections versus observations. Again, the reviewer provides no citations.
5	42	4	The authors provide a relatively accurate survey of results regarding hurricane numbers and landfall frequency, which have indeed not shown any trends. But their analysis of hurricane intensity, which has been shown in many studies to increase, is lacking...the chart showing just estimated windspeeds of the top ten landfalling storms is really weak given the analytical talents of the author team. They also do not provide any discussion of the physical basis for why hurricane numbers may not be changing while the intensity of the strongest hurricanes is expected to increase, nor analyze any data in the context of those conclusions. The challenge for global intensity metrics is that the satellite record prior to 1980-1990 (experts disagree on the data quality

DOJ_00000732

			during this period) is inadequate, which is why we focus on the Atlantic hurricane data. Also there is no theory for hurricane number; that is a topic associated with substantial uncertainty.
6	47	5	Long term persistence is not a recognized property or phenomenon associated with rainfall data. The use of such a statistical technique, especially one that is not widely recognized or used in the hydroclimate community, demands additional justification. We have rewritten the text to remove specific reference to LTP.
6	53	4	The authors have cherry picked results throughout this section. For example, they have selected only a few quotes from IPCC and NCA describing extreme heat. The absolute single daily maximum temperature for a given year, for example, is a poor statistic for assessing statistical changes in extreme heat (it woudl be like comparing the tallest person in each country to try to calculate change in average height). A complete and comprehensive review of the underlying assessments and the data it cites clearly shows that extreme heat has been increasing in North America. The reviewer fails to identify any data or conclusion from the IPCC or NCA that differs from our assessment, and fails to cite any sources to justify this comment.
6	56	1	The "climate less prone to extremes" is a misleading statement. If minimum temperatures are increasing faster than maximum temperatures (which is an expectation of climate change based on basic physical principals), then the difference between warm and cold extremes on many timescales is expected to decrease. There are reasonable points to be made regarding observational deficiencies, regional variations in extreme events, and the potential benefits of reductions in extreme cold, rather than coming up with misleading statistics. But we show that extreme heat has also declined since the 1930s – Figures 6.3.1 and 6.3.3 refute the reviewer's statement.
6	58	3	The NCA5 heading is not a controversial statement, it simply says that things are changing, which they are by the author's own admissions and graphs. It does not suggest pervasive positive trends, as the authors suggest it does. We're not sure what sentence the reviewer is referring to.
6	61	3	The statistical techniques used in the 2019 paper are highly non-standard for evaluating precipitation statistics, and the 2024 results have not been peer reviewed. The results reported in the NCA and IPCC and the underlying studies have clearly demonstrated that extreme precipitation is increasing. The 2019 paper uses ordinary least squares to compute the trend, and a standard variance estimator from the econometrics literature to assess significance. As we point out, we also find evidence of increasing precipitation averages and extremes but only when selecting certain start dates.

DOJ_00000733

6	61	7	The relevance of the paragraph on 19th century and paleoclimatic rainfall events is unclear. If anything, the fact that such extremes have occurred in the past argues for more aggressive adaptation measures to ensure that damages won't be as high if they happen again (even notwithstanding potential changes in risk due to climate change). Note, however, that additional context is provided in the box that follows two pages later. We agree that discovery of extreme events in the 19th century records indicates that disaster planning may need to encompass a wider range of risks.
6	62	1	The choice of looking at (only) 5-day precipitation totals is questionable. Most rainfall events, including the most extreme and damaging preciptation events, are typically on a daily timescale. Again, the reviewer provides no citations or evidence. Our results are robust to different day intervals, and we refer to 1- and 2-day results as well.
6	68	3	Perhaps this is more germane to the sea level rise section, but nuisance (high tide) flooding due to sea level rise has been observed across much of the united states. This is a topic we did not address.

DOJ_00000734

From: Ross McKitrick <ross.mckitrick@gmail.com>
Sent: Friday, May 23, 2025 3:53 PM
To: Travis Fisher; Judith Curry; Roy W. Spencer; John Christy; Steven Koonin; Josh Loucks
Subject: 04.PostSecReview folder

I've opened a new folder called 04.PostSecReview to hold the next stage of drafts.
https://www.dropbox.com/scl/fo/x726u2iupkuts86qhehjw/AObqNt2zetg0YDO2BbABk-c?rlkey=0a6elgto9k5y4v6l6m1ojh06f&st=s1oswa4o&dl=0
I'll also send a share email

The doc that's in there is called ReportDraftMay23[Ref1to3]
It includes the text Judy flagged as missing from the previous draft Ch 4 and I have cleaned up the reference lists for Chapters 1 to 3, hence the file name. Josh and/or Travis if you get through the reference lists for any other chapters please post an updated version with the name changed to indicate which chapters you finished. I am going to start working on the lists for the Part III chapters.

Regarding the references, does anyone know what Angert 2004 is? The citation was

> There was also a substantial additional reduction in atmospheric CO2 after the 1991 eruption of Mt. Pinatubo, a curious result that has yet to be explained (Angert et al., 2004).

but I don't have the reference anywhere.

DOJ_00000735

From: Ross McKitrick [ross.mckitrick@gmail.com]
Sent: 5/18/2025 4:41:06 PM
To: Travis Fisher [travis.scott.fisher@gmail.com]; Steven Koonin [steven.koonin@gmail.com]; John Christy [climateman60@gmail.com]; Roy W. Spencer [roywspencer@hotmail.com]; Judith Curry [curry.judith@gmail.com]
Subject: Work assignment for Travis - Reference lists
Attachments: RM.References.docx

Hi Travis

1 In the 01.Report Drafts folder Chapters 10 & 11 are now merged. Please renumber Ch 12 to 11 and 13 to 12.

2: References
I've attached a list of references I was compiling earlier in the project when I thought there would just be one list at the end. But instead we will have reference lists at the end of each chapter. At this point there are conflicting formats. Some are entered as superscripts and some as (name, date) insertions. I'd like you and Josh to go through every chapter and put all the citations into a common format. You can save the file thus edited with a [REF] insertion in the name.

The format in the text should be (Last name date) with a reference list at the end of each chapter. For the in-text citation note the following examples

... Connolly et al. (2023) found that ...
... Pielke and Ritchie (2020) reported new studies ....
... to be intercalibrated with the prior system (Zacharias 2014, Scafetta et al. 2019).
... distributed over the daily solar cycle (Curry and Webster, 1999).

Keys:
(Last name date) do not include first initials and no comma between name and date
If two names include both
If 3 or more, include the first and then et al. (period after al)
If the citation is the subject of a sentence only the year goes in brackets.

Where there is a superscript you'll need to convert to the inline citation and move the footnoted reference to the end of the chapter.

references:
Use the full name of journals, not short forms (*Journal of Climate* not *J Clim*)
Journal names and book names in italics
The year goes after the author name(s) and before the article title
If there are more than 4 authors list the first 3 and then say et al.
Author names: first entry is Last name, First name; then the rest are First name, last name
If the full first name is shown, leave it as such, if only the first initial(s) is shown leave it. I prefer the full first names but you don't need to look up missing names.

Zelinka, M. D., T. A. Myers, D. T. McCoy, et al. (2020). Causes of higher climate sensitivity in CMIP6 models. *Geophysical Research Letters* 47, e2019GL085782. https://doi.org/10.1029/2019GL085782

The citation detail depends a bit on the age of the article. It used to be *Journal* Vol(issue) but now the most important identifier is the DOI number and/or hyperlink so an active hyperlink should be included wherever possible.

The reference list should be alphabetized. If there are multiple citations for the same author(s) and year use a,b,c etc., as in Lewis (2022a), Lewis (2022b) or the in-line citation and then carry the a or b to the year in the corresponding reference list entry.

As chapter reference lists have grown some of the underlying text may have been removed so there may be entries in the existing reference lists that are no longer needed, and there may be in-line citations with no reference in the list. Check my master list, otherwise flag citations for which no reference is provided.

For the text submitted using superscript references, after the first appearance of a citation subsequent superscripts will have a footnote saying something like *ibid* or *op. cit*. Those need to be converted to the corresponding (name date) citation.

The final formatting will involve indenting the 2nd and subsequent lines of reference list entries:

Zhao, Qi et al. (2021), "Global, Regional, and National Burden of ?
Temperatures from 2000 to 2019: A Three-Stage Modelling Stu
2021), https://doi.org/10.1016/s2542-5196(21)00081-4.

For this to work will require not putting line breaks in reference list entries.

Thanks and if you run into any questions please let me know.

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DOJ_00000744

Zhao, Xiaobing, Mason Gerety, and Nicolai V. Kuminoff (2018) Revisiting the temperature-economic growth relationship using global subnational data. *Journal of environmental management*, 223:537–544, 2018.

DOJ_00000745

From: Steven Koonin [steven.koonin@gmail.com]
Sent: 6/3/2025 9:53:20 PM
To: 'Judith Curry' [curry.judith@gmail.com]; 'Ross McKitrick' [ross.mckitrick@gmail.com]
CC: 'Roy W. Spencer' [roywspencer@hotmail.com]; 'John Christy' [climateman60@gmail.com]; 'Travis Fisher' [travis.scott.fisher@gmail.com]; 'Josh Loucks' [loucksj14@gmail.com]
Subject: RE: NCA5 complete text
Attachments: ~WRD0758.jpg

Yes, I think it's Chapters 1,2,3 and selected material from other chapters that's particularly egregious and where we have cred to criticize

SEK

From: Judith Curry <curry.judith@gmail.com>
Sent: Tuesday, June 3, 2025 5:51 PM
To: Ross McKitrick <ross.mckitrick@gmail.com>
Cc: Roy W. Spencer <roywspencer@hotmail.com>; Steven Koonin <steven.koonin@gmail.com>; John Christy <climateman60@gmail.com>; Travis Fisher <travis.scott.fisher@gmail.com>; Josh Loucks <loucksj14@gmail.com>
Subject: Re: NCA5 complete text

I think we also need to do ch 3, which includes climate sensitivity, attribution etc

On Tue, Jun 3, 2025 at 1:29 PM Ross McKitrick <ross.mckitrick@gmail.com> wrote:

> Downloadable version is available here
> https://nca2023.globalchange.gov/downloads/NCA5_2023_FullReport.pdf

--

Judith Curry, President
CFAN - Climate Forecast Applications Network
Reno, NV USA
curry.judith@cfanclimate.com | +1.404.803.2012
http://www.cfanclimate.net

From: Judith Curry <curry.judith@gmail.com>
Sent: Tuesday, June 3, 2025 5:51 PM
To: Ross McKitrick
Cc: Roy W. Spencer; Steven Koonin; John Christy; Travis Fisher; Josh Loucks
Subject: Re: NCA5 complete text

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Reno, NV USA
curry.judith@cfanclimate.com | +1.404.803.2012
http://www.cfanclimate.net

From: Ross McKitrick <ross.mckitrick@gmail.com>
Sent: Tuesday, June 3, 2025 4:29 PM
To: Roy W. Spencer; Judith Curry; Steven Koonin; John Christy; Travis Fisher; Josh Loucks
Subject: NCA5 complete text

Downloadable version is available here
https://nca2023.globalchange.gov/downloads/NCA5_2023_FullReport.pdfÂ

From: Ross McKitrick <ross.mckitrick@gmail.com>
Sent: Monday, July 21, 2025 2:12 PM
To: Judith Curry; Roy W. Spencer; John Christy; Steven Koonin; Travis Fisher; Josh Loucks; Cohen, Seth
Subject: climate disasters so far in 2025

An interesting insight from RPJr
https://rogerpielkejr.substack.com/p/human-progress-versus-climate-evangelism

~2,200 people worldwide died in catastrophes related to extreme weather events during the first six months of the year. On the one hand, ~2,200 deaths are a lot and every loss of life is tragic. On the other hand, in the context of historical losses related to weather extreme, on a planet of 8.2 billion people, ~2,200 deaths is incredibly low. Historically low, in fact.
... we can conclude with some confidence that the first half of 2025 has seen the fewest deaths related to extreme weather of any January-June this century. **I'd go so far as to suggest that it is likely that the first half of 2025 has seen the fewest deaths related to extreme weather of any half year in recorded human history**,

DOJ_00000749

From: John Christy <climateman60@gmail.com>
Sent: Tuesday, July 8, 2025 4:31 PM
To: Ross McKitrick
Cc: Steven Koonin; Travis Fisher; Roy Spencer; Judith Curry; Josh Loucks
Subject: Re: Washington Post on your appointment at DOE

Had the identical CNN email, word for word sent to me.

John C.

On Tue, Jul 8, 2025 at 2:20 PM Ross McKitrick <ross.mckitrick@gmail.com> wrote:
And as for the question, if only you'd written a book explaining your views.

On Tue, Jul 8, 2025 at 3:15 PM Steven Koonin <steven.koonin@gmail.com> wrote:
And WaPo weighs in.

Steven E. Koonin

Begin forwarded message:

> **From:** "Spring, Jake" <Jake.Spring@washpost.com>
> **Date:** July 8, 2025 at 15:10:55 EDT
> **To:** steven.koonin@gmail.com
> **Subject: Washington Post on your appointment at DOE**
>
> Dear Dr Koonin,
>
> I'm a reporter with The Washington Post and am wondering if you can confirm your hiring by the DOE? What is the role you'll be taking there? I'm looking to confirm the story on your hiring by New York Times.
>
> Do you agree with your characterization in the NYT? Do you reject the scientific consensus on climate change? Were you brought on to help work on the endangerment finding reconsideration?
>
> If you'd be open to speaking to me, my number is 202 870 0949 and my signal is jspring.99
>
> I'm open to discuss speaking on background if you prefer.
>
> Best,
> Jake

Jake Spring
The Washington Post
(202) 870-0949
jake.spring@washpost.com

From: Ross McKitrick <ross.mckitrick@gmail.com>
Sent: Tuesday, July 8, 2025 3:20 PM
To: Steven Koonin
Cc: Travis Fisher; Roy Spencer; Judith Curry; John Christy; Josh Loucks
Subject: Re: Washington Post on your appointment at DOE

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Steven E. Koonin

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>
> Best,
> Jake
>
> Jake Spring
> The Washington Post
> (202) 870-0949
> jake.spring@washpost.com

From: Ross McKitrick <ross.mckitrick@gmail.com>
Sent: Tuesday, July 8, 2025 3:19 PM
To: Steven Koonin
Cc: Travis Fisher; Roy Spencer; Judith Curry; John Christy; Josh Loucks
Subject: Re: Washington Post on your appointment at DOE

You've got star power.

On Tue, Jul 8, 2025 at 3:15 PM Steven Koonin <steven.koonin@gmail.com> wrote:
And WaPo weighs in.

Steven E. Koonin

Begin forwarded message:

> **From:** "Spring, Jake" <Jake.Spring@washpost.com>
> **Date:** July 8, 2025 at 15:10:55 EDT
> **To:** steven.koonin@gmail.com
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> Best,
> Jake
>
> Jake Spring
> The Washington Post
> (202) 870-0949
> jake.spring@washpost.com

From: Steven Koonin <steven.koonin@gmail.com>
Sent: Tuesday, July 8, 2025 3:15 PM
To: Travis Fisher
Cc: Roy Spencer; Ross McKitrick; Judith Curry; John Christy; Josh Loucks
Subject: Fwd: Washington Post on your appointment at DOE

And WaPo weighs in.

Steven E. Koonin

Begin forwarded message:

> **From:** "Spring, Jake" <Jake.Spring@washpost.com>
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> I'm open to discuss speaking on background if you prefer.
>
> Best,
> Jake
>
> Jake Spring
> The Washington Post
> (202) 870-0949
> jake.spring@washpost.com

From: Ross McKitrick <ross.mckitrick@gmail.com>
Sent: Friday, August 15, 2025 10:36 AM
To: Judith Curry; Roy W. Spencer; John Christy; Steven Koonin
Subject: cherry-picking, bad science and bias

No I'm not talking about what the other guys are accusing us of, I'm talking about what they've been up to. It's a remarkable breaking story. As Judy just noted Roger Pielke Jr has an overview here https://rogerpielkejr.substack.com/p/too-big-to-fail

In 2024 a garbage study by Kotz et al from the Potsdam Institute was published in Nature (of course) claiming global warming would wipe out so much growth by 2100 we'd be far better off capping emissions and preventing 2C blah blah blah. Way outside the mainstream of economic studies on the subject. One of our internal DoE reviewers asked us to include the Kotz study in our review, which I declined to do. I doubt anyone in the public review will make the same request now.

Of course all the usual press suspects hyped the Kotz paper but more ominously a group called the Network for Greening the Financial System inhaled it and instantly made it the basis of new global central bank climate risk regulations with massive financial consequences for noncompliant banks. The US Fed is not part of NFGS but a lot of world central banks are. (Thanks to lobbying and arm-twisting by the moron we just elected Prime Minister.)

The Lotz study was obvious rubbish and within a month Nature received the first of a series of comments showing fundamental errors in it. One came from the Banking Policy Institute, story here: https://bpi.com/the-flawed-ngfs-damage-function-is-even-more-flawed-than-we-thought/

More followed. nature magazine withheld the comments but did post a warning to readers that the study had been challenged. NGFS ignored the warning, as did the Congressional Budget Office which used it for their own bit of fearmongering:
https://www.cbo.gov/publication/61146

This month nature finally published the critiques, and they are ruinous to Kotz et al. But in another twist, nature sat on the critiques long enough for Kotz et al to ginn up an unpublished paper offering a revised version of their model that supposedly generates the same results as previously, only under new assumptions. The critics of the original study have trashed that one as well. And NFGS has not acknowledged any of this.

The whole episode reeks of failure by NFGS and the CBO to practise elementary due diligence. The consequences could well give rise to a class action lawsuit.

On the same topic, a former PhD student and I just published a paper in Climate Change Economics on climate change and growth. We built 2 new long term global data sets and showed (yet again) there's no significant impact of warming on growth, the point estimates are small and positive, and poor countries are just as likely as rich countries to benefit. We went through 3 rounds of rather hostile peer review but rebutted all the criticisms. At one point we were asked to include Kotz in our lit review which is when I first learned about the paper and the controversies.

Ross

From: Ross McKitrick <ross.mckitrick@gmail.com>
Sent: Wednesday, May 21, 2025 1:04 PM
To: Roy W. Spencer; Judith Curry; John Christy; Steven Koonin
Subject: McKitrick bio

Ross McKitrick, Ph.D., is a Professor of Environmental Economics at the University of Guelph in Ontario, Canada. He holds a BA in economics from Queen's University, and an MA and Ph.D. in economics from the University of British Columbia. He has published widely in both economics and physical science journals on topics related to climate change, pollution and public policy. His book *Economic Analysis of Environmental Policy* was published by the University of Toronto Press in 2010. In addition to his economics research his background in applied statistics has led him to collaborative work across a wide range of topics in the physical sciences including paleoclimate reconstruction, malaria transmission, surface temperature measurement, climate attribution methodology and climate model evaluation. Professor McKitrick has made many invited academic presentations around the world, and has testified before the US Congress and committees of the Canadian House of Commons and Senate.

From: Ross McKitrick [ross.mckitrick@gmail.com]
Sent: 5/17/2025 5:36:12 PM
To: Travis Fisher [travis.scott.fisher@gmail.com]; Roy W. Spencer [roywspencer@hotmail.com]; John Christy [climateman60@gmail.com]; Steven Koonin [steven.koonin@gmail.com]; Judith Curry [curry.judith@gmail.com]
Subject: New econ ch with tipping points
Attachments: 12 Climate, Economy and SCC.May17.docx

There's a new version of the Econ-SCC chapter with a sectionÂ added on tipping points that Judy and I assembled. It's dated May 17 and is attached and is in the 01.Drafts folder.Â

12 Climate change, the economy and the Social Cost of Carbon

12.1 Climate change and economic growth

12.1.1 Overview: climate is a relatively minor issue for a modern economy

It has long been noted that economies tend to do poorly in very cold and very hot regions, with the optimum somewhere in between (Nordhaus 2006). Temperature-sensitive economic activity migrates, whenever possible, to where it is best suited, and society always adapts to the local climate. Based in part on these observations, in 1992 Thomas Schelling, then President of the American Economic Association, argued that any effects of climate change on US economic activity would be small relative to the many other changes that would happen.

> ... Manufacturing rarely depends on climate, and where temperature and humidity used to make a difference, air conditioning has intervened. When Toyota chooses among Ohio, Alabama, and Southern California for locating an automobile assembly, geographical considerations are important, but not because of climate... Finance is little affected by climate; similarly for health care, or education, or broadcasting. Transportation can be affected, but improvements in all-weather landing and take-off in the last 30 years are greater than any differences that climate makes. If the average effect is a warming, iced waterways and snow removal may decline in importance. Construction is affected, mainly by cold, and if the average effect is in the direction of warming, construction may benefit slightly.
>
> It is really agriculture that is affected. But even if agricultural productivity declined by a third over the next half century, the per capita GNP we might have achieved by 2050 we would achieve only in 2051. ...
>
> **I conclude that in the United States, and probably Japan, Western Europe, and other developed countries, the impact on economic output will be negligible and unlikely to be noticed.**
> (Schelling 1992, emphasis added)

Thirty years later virtually the identical point was made by the IPCC itself in the Fifth Assessment Report:

> **For most economic sectors, the impact of climate change will be small relative to the impacts of other drivers.** Changes in population, age, income, technology, relative prices, lifestyle, regulation, governance, and many other aspects of socioeconomic development will have an impact on the supply and demand of economic goods and services that is large relative to the impact of climate change.
> (Arent et al. 2014, emphasis added)

That statement is validated by experience. Since 1900, the average global surface temperature anomaly warmed 1.3°C, about as much as the IPCC predicts will occur in the next century under a moderate emissions scenario. But even as the globe warmed and the population quintupled, humanity prospered as never before. For example, global average lifespan went from thirty-two years to seventy-two years, economic activity per capita grew by a factor of seven, and the death rate from extreme weather events plummeted by a factor of fifty!

While extreme weather events are costly, in all modern economies they are becoming steadily less and less important (Formetta and Feyen 2019). Since 1990 weather-related disaster losses have declined as a proportion of global GDP (Pielke Jr 2018, 2020) as have mortality risks (Formetta and Feyen 2019). While economic weather-related insurance payouts are rising, this is fully explained by the growth in the size of the economy and the value of the insured asset stock. Past increases in episodes extreme weather have not had a significant effect (positive or negative) on the market value of insurance firms (Hu and McKitrick 2015). Nor have past extreme weather events had a significant effect on US banks' performance (Blickle et al. 2021).

For these reasons, economists have long been reluctant to endorse attempts to "stop" climate change or even aggressively reduce GHG emissions because the costs would not be worth it. As one critic of the economics of climate policy put it:

> Mainstream climate economics takes global warming seriously, but perplexingly concludes that the optimal economic policy is to almost do nothing about it... The contrast is striking. While climate science is sending out loud-and-clear messages that fossil-fuel disinvestment must start now, letting go of coal and oil and diverting resources into renewable energy technology systems, to keep warming below the 2°C limit (IPCC 2014), mainstream climate economics claims that overly ambitious climate targets will unnecessarily hurt the economy and immediate de-carbonization is too expensive. Most climate economists thus recommend humanity to just wait-and-see.
> (Storm 2017)

The mainstream economics position on the climate policy question is best represented by the findings over the past three decades from Integrated Assessment Models (IAMs) of climate change policy, for which Yale economist William Nordhaus was awarded the 2018 Nobel Memorial Prize in economics. IAMs combine economic, climate, and social data into a unified framework for simulating climate damages and evaluating the optimal policy response (Resources for the Future 2025). Nordhaus' work has generally supported modest global climate policy, with aggressive measures largely deferred to later in the century. Nordhaus developed the so-called Dynamic Integrated Model of the Climate and Economy model, or DICE, in the early 1990s (Nordhaus 1993) to study the interaction between climate change, climate policy, and global economic growth over long times. DICE assumes global emission control can be coordinated at no cost and asks what the optimal policy target should be. The climate component of the DICE model is based on simplified climatological modeling. The version of DICE at the time of Nordhaus' Nobel Prize award was described in Nordhaus (2018);it had a climate sensitivity parameter of 3.1°C for CO_2 doubling, consistent with the best estimate in contemporary IPCC reports (3.0°C).

The baseline (no policy) scenario incurs only $0.4T in global abatement costs and leads to $134.2T (trillion dollars) in global climate damages for a total cost of $134.6T. The climate model component of DICE projects 4.1°C warming by 2100 relative to preindustrial temperatures. Note that this is a higher estimate of warming than many IPCC climate models. (AR6 offers 2.7°C in 2100 under a moderate emissions scenario.)

The Optimal Policy scenario barely deviates from the business-as-usual path. It aims for +3.5°C warming, in other words we scale back only the lowest-value fossil fuel use and otherwise just live with almost all the warming. This suggests that most CO_2 emissions are less harmful than the policies that would be necessary to abate them. Trying to prevent warming causes costs quickly to outstrip the benefits. Pursuing a goal of capping warming at 2.5°C creates total costs of $177.8T,

DOJ_00000761

which is $43.2T worse than doing nothing at all. Nordhaus didn't evaluate trying to reach a Paris-type target of 1.5°C warming but it would be even worse.

A subsequent edition of DICE includes higher assumed damages from warming which, not surprisingly leads to more aggressive policy recommendations, as explained in the section below on the Social Cost of Carbon.

12.1.2 Empirical analysis of climate change and economic growth

Many other studies have used econometric methods applied to historical data, instead of IAMs, to study the potential impact of climate change on economic growth. Dell et al. (2012, herein DJO12) was an influential study that used a multi-country panel of national-level data spanning 1950 to 2005, in which they matched climate and economic data by averaging temperature from the local grid cell level up to the national level using population weights. They found that warming yields an insignificant positive effect on income growth in rich countries but a significant negative effect in poor countries. Moore and Diaz (2015) modified the DICE model to take that finding into account and concluded that it implied a dramatically higher Social Cost of Carbon due to the compounding effects of income loss over time.

A large subsequent literature has debated the robustness of the DJO12 findings. Burke et al. (2015) analyzed a global panel with temperatures averaged up to the national level and found a negative effect on growth from warming in rich and poor countries alike when the national average temperature is above 13°C. Zhao et al. (2018) used the G-Econ data set of Nordhaus (2006), which breaks economic activity down to the grid cell level, replicated DJO12-type results on the same subset of countries as used in DJO12 but then showed that on the full global sample warming increases growth in rich countries and poor countries alike, though the positive effect in the latter group is confined to where local temperatures are below about 16°C. Greβer et al. (2021) developed a regional economic data set for 1,542 sub-national regions around the world between 2005 and 2015 and found temperature had no effect on growth. Yang et al. (2023) updated the DJO12 data set and applied an estimator robust to mixed sample frequencies, finding that while temperature shocks exerted a temporary effect on income levels, they did not have a significant lasting effect on growth rates.

Newell et al. (2021) noted that there is no underlying theory to guide econometric model specification in this literature. Taking into account the arbitrary choices of which explanatory variables to include they identified over 800 possible model specifications. Using the Burke et al. (2015) data they used an estimation method that accounts for model uncertainty and found that the model form preferred by Burke et al. (2015), which implied negative effects of warming on growth even in rich countries, is explicitly excluded by the optimal model selection algorithm. Overall they could not detect a temperature effect on GDP or GDP growth, and they estimated the 95% confidence interval for the impact on global growth as of 2100 even under the exaggerated RCP8.5 warming scenario spans −86 percent to +388 percent. In other words the net effect is likely positive but too uncertain to distinguish from zero.

Barker (2023) criticized the DJO12 assumption that countries can be grouped into fixed "poor" and "rich" categories based on their incomes many decades ago. He noted that many countries were once poor but became rich over time, and if this is taken into account the original temperature effects reported by Dell et al. became small and insignificant.

Berg et al. (2023) argued that countries shouldn't be grouped into large Rich/Poor categories because they are too heterogeneous. They instead estimated country-specific temperature response

DOJ_00000762

coefficients then grouped countries with similar response coefficients into small panels. They separately estimated responses to global and idiosyncratic local temperature shocks to better identify the climate signal in weather data. Overall they found countries experiencing negative effects of warming on growth outnumbered those experiencing positive effects, but only temporarily: eventually the effects reverse such that about twice as many countries experience a net positive growth effect. They also found global (as opposed to local) temperature changes are much more likely to benefit growth in poor countries than rich ones. In a simulation to 2100 even using the extreme RCP8.5 scenario they computed the average global GDP loss would be only 1.9% compared to a scenario with no warming. That is, instead of the economy growing 400% it would grow 398%. The implication of Nordhaus' earlier analysis is that trying to prevent the warming would lead to far less than 398% growth.

To summarize, economists have long considered climate a relatively unimportant factor in economic growth, a view echoed by the IPCC itself in the Fifth Assessment Report. Mainstream climate economics has recognized that CO_2-induced warming may have some negative economic effects but they are too small to justify aggressive abatement policy, and trying to "stop" or cap global warming even at levels well above the Paris target would be worse than doing nothing. An influential study in 2012 suggested that global warming would harm growth in poor countries but the finding has subsequently been found not to be robust. Studies that take full account of modeling uncertainties either find no evidence of a negative effect on global growth from CO_2 emissions or find poor countries as likely to benefit from it as rich countries.

The expectation that significant global warming would have a small impact on the U.S. economy was acknowledged quietly by the Biden Administration, even as the President was proclaiming a climate emergency. The following figure, from a 2023 OMB-CEA report, shows the expected decrement in U.S. GDP as a function of temperature rise. The colored lines show the results of a dozen peer-reviewed published studies while the solid black line is their average. The figure could be summarized as "a few percent impact for a few degrees of warming". Given that the economy's annual growth rate is expected to be 1-2 percent, the impact of a warming globe is indeed negligible.

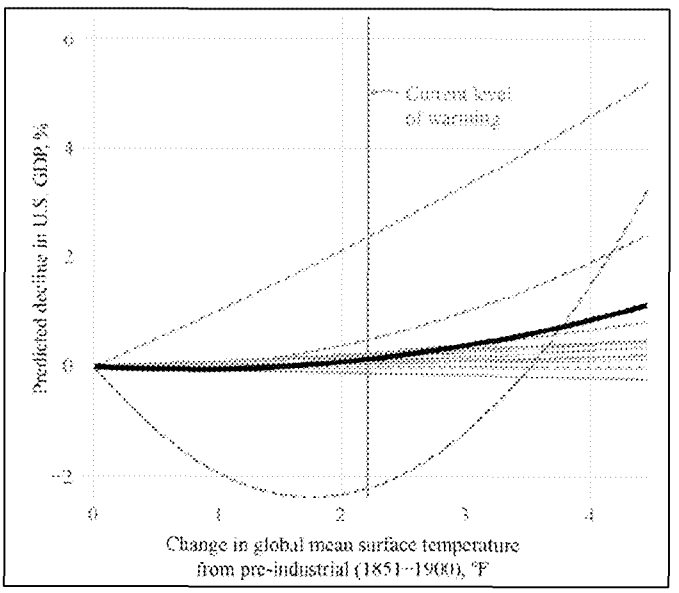

Figure 12.1: Decline in US GDP per degree of warming. Source: XX

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12.2 Models of the Social Cost of Carbon

The Social Cost of Carbon (SCC) is a tool for quantifying the economic impact of carbon dioxide emissions, helping policymakers weigh the costs and benefits of climate policies. It estimates the damage caused by emitting one additional ton of CO_2, expressed in dollars. More formally, the SCC is the discounted present value of the current and future marginal loss of economic welfare due to an additional ton of CO2 entering the atmosphere.

> *Sidebar: finding the optimal emissions price*
> On its own the SCC is not the appropriate price to attach to CO_2 emissions for the purpose of optimal emissions control but it can be converted into an optimal tax rate by scaling it by a parameter called the Marginal Cost of Public Funds (MCPF). The theory behind this was first derived by Sandmo (1975) and has been reiterated many times since then by other economists working on the topic (e.g. Parry et al. 1999). The MCPF is the cost in terms of lost private economic welfare of raising public revenue by one dollar and always exceeds unity. If a jurisdiction does not use a carbon tax, this formula still indicates the upper bound on the amount emitters should spend on abatement options at the margin along the optimal policy path. Regulations should be imposed only insofar as they do not impose marginal abatement costs in excess of the optimal tax rate.

12.2.1 Estimating the SCC

Although the literature refers to "estimates" of the SCC, it is not estimated in the way other economic statistics are estimated. For instance, data on market transactions including prices and quantities can be used to estimate the current inflation rate or the growth rate of per capita real Gross Domestic Product, and there are well-understood uncertainties associated with these quantities. But there are no market data available to measure many if not most of the marginal damages or benefits believed to be associated with CO2 emissions, so these need to be imputed using economic models.

For example, an influential component of some SCC calculations is the perceived social cost associated with changed risk of future mortality due to extreme weather. There is no market in which people can directly attach a price to that risk. At best economists can try to infer such values by looking at transactions in related markets such as real estate or insurance, but isolating the component of price changes attributable to atmospheric CO2 levels is very difficult.

Economists use IAMs to compute the SCC. Two of the best known are the Climate Framework for Uncertainty, Negotiation and Distribution ("FUND", Tol 1997) and Nordaus' DICE. IAMs embed a "damage function" or set of functions relating ambient temperature to local economic conditions. The assumptions embedded in the damage function will largely determine the resulting SCC. IAMs also assume a long-term discount rate or, as in DICE, compute the optimal internal discount rate as part of the solution.

One approach to developing a damage function is to begin with estimates of the costs (or benefits) of warming in specific sectors in countries around the world and aggregate up to a global amount. This was the approach used in FUND. An alternative approach is to develop a simple equation that penalizes global income according to a simple quadratic function of the average global temperature. This approach was used in DICE. In the case of the FUND model many hundreds of parameters had to be selected, whereas in DICE only three were needed and were originally chosen to assign a predetermined penalty (1.2%) to global output as of 3°C warming, with a quadratic term implying

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that damages grow with the square of the global average temperature anomaly. Barrage and Nordhaus (2024) recently changed the parameters to increase the penalty at 3°C to 1.6%, and added a discrete additional 1.0% GDP penalty at 3°C warming to account for "tipping points" (discrete large-scale environmental changes triggered by crossing a warming threshold) and a "judgmental adjustment" of 0.5% for excluded impacts at 3°C warming. Not surprisingly the newer version of DICE generates much higher SCC estimates than before.

The concepts of estimation and uncertainty do not readily apply to SCC calculations. By comparison, the question of whether precipitation has trended up or down along the South Carolina coast for the past hundred years can be addressed by collecting rainfall data, estimating a trend parameter and calculating statistical confidence intervals using methods with well-understood mathematical properties. In this way uncertainty can, in principle, be resolved by collecting more data and applying more accurate methods. But no amount of data collection can change the fact that many components of the SCC are unknown and rely on judgment and opinion based on knowledge of the underlying literature on the physical effects of climate change.

SCC calculations are thus best thought of as "if-then" statements: *if* the following assumptions hold, *then* the SCC is $X per tonne. The list of 'if' statements includes the premise that the world's climate and economy work according to the representation in the IAM. One way this may fail to hold is in the timing of warming. Every IAM assumes a value of the Equilibrium Climate Sensitivity (ECS), which controls the amount of warming that results from CO2 emissions and can be freely varied for the purpose of generating a distribution of SCC values associated with uncertainties over ECS. But as Roe and Baumann (2013) pointed out, time-to-equilibrium increases with the square of ECS, so an upward adjustment of the ECS parameter without an appropriate slowing down of the adjustment process can yield distorted present value damage estimates. In particular, the upper tail of warming associated with some commonly-used ECS distributions is physically impossible for even a thousand years into the future (Roe and Baumann 2013) yet in an IAM would be realized within a couple of centuries. Failure to align ECS with time-to-equilibrium will lead to an overestimate of the SCC value.

12.2.2 Variations in the SCC

Every level of the IAM calculation includes assumptions, some more influential than others. Key assumptions include the following.

- The discount rate: Climate damages accrue over a long time horizon, and costs a century or two in the future need to be discounted to the present. The higher the discount rate the smaller the present value of future damages and vice versa. The discount rate represents the opportunity cost of spending money today rather than investing it and then having more to spend tomorrow. Some economists have argued for the use of very low discount rates in SCC calculations, resulting in policy recommendations that favor relatively large immediate investments in CO2 emission reductions. The downside is that other investments could potentially earn a larger rate of return for society.

- Equilibrium Climate Sensitivity: IAMs have customarily employed a value of 3.0°C or 3.1°C following the IPCC's guidance. Empirically-estimated ECS values tend to be lower than this (see Chapter 9). Dayaratna et al. (2017, 2020, 2023) have shown that use of lower empirically-derived ECS values dramatically lower the resulting SCC estimate, even when low discount rates are used.

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- Damage function coefficients: IAMs assume CO2 and warming cause net harms that increase exponentially with temperature. More recently, IAMs have also incorporated effects from assumed potential climate tipping points. The FUND model took limited but explicit account of CO_2 fertilization effects in agriculture. Since the coefficients were selected prior the publication of the current evidence of global greening and the magnitude of benefits to crops from elevated CO_2 (see Chapters 2 and 10) the growth effects are likely understated. The DICE model (and others) did not explicitly include any CO_2 fertilization benefit, except to the extent it was taken into account in the literature consulted when picking the damage function coefficients. The damage function in FUND contains a region in which low warming yields net benefits in many regions, a finding which is supported by econometric models of warming and growth (Berg et al. 2023) and econometric simulations of agricultural changes (McKitrick 2025). The DICE damage function, by construction, rules out net benefits at any warming level.

- Emission scenarios: IAMs generate SCC estimates that increase as the pre-existing concentration of CO_2 increases. Consequently the value of damages later in the century will be higher, depending on the assumed baseline emissions over the coming decades.

- Abatement costs: IAMs represent the cost to the economy of reducing CO_2 emissions. If CO_2 emission reductions are assumed to be inexpensive, then the model will conclude that the optimal policy should aim for deeper emission cuts and vice versa.

It is informative to ascertain whether SCC results are invariant to changes in some assumptions. But when different assumptions result in higher or lower SCC values, the change in the SCC value does not provide *prima facie* evidence about the validity of the assumptions. For example, in 2023 the US Environmental Protection Agency raised its preferred SCC value about 5-fold over the estimates it had issued ten years earlier. This is not because new data had been collected or better mathematical methods had been invented, but because new assumptions had been used, and the validity of those assumptions was a separate question. One was that global agricultural damages were far higher than previously assumed, based on an analysis in Moore et al. (2017). But as discussed in Chapter 10, McKitrick (2025) showed that Moore et al. (2017) had used a database in which half the CO_2 change observations were missing. When as many of those observations as possible were recovered from underlying sources and the analysis was rerun, the projected crop yield losses disappeared and turned into gains at all warming levels. Hence the portion of the EPA's SCC revision attributable to agricultural yield losses was unwarranted.

12.2.3 Evidence for low SCC

Chapter 2 reviewed evidence on climate change and greening, and Chapter 10 looked at climate change and US agriculture. Evidence shows that CO_2 fertilization has a stronger beneficial effect on agriculture than was known at the time that IAMs like DICE and FUND were parameterized. In particular Haverd et al. (2020) found the observed CO_2 fertilization rate has been almost double what had been predicted by crop models. Dayaratna et al. (2023) used the updated empirical ECS distribution estimate of Lewis (2022), which assimilates modern instrumental and paleoclimatic temperature records, and allowed for a 30 percent gain in the CO_2 fertilization benefit in the FUND model, and found that, even at a low discount rate of 2.5 percent, the median SCC as of 2050 is only $18.67, with a 24 percent probability of the true value being negative. At a five percent discount rate the median SCC value is negative until the mid-2040s and at 2050 was only $0.37 with a 49 percent probability of being negative. Thus, under reasonable assumptions a mainstream IAM using

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updated scientific inputs yields evidence consistent with the SCC not being significantly greater than zero.

It should also be noted that the SCC is focused on the social costs of CO_2 emissions from fossil fuel use. It does not measure the private marginal benefits to consumers and society from the availability of fossil fuels. Public willingness to pay for fuels of all types indicates the value to society of reliable, abundant fossil energy. Tol (2017) estimates that the private benefit of carbon is large relative to the social cost. This can be illustrated by noting that the price of a gallon of gas indicates the marginal value to the consumer of the fuel. Suppose we assume a relatively high Social Cost of Carbon of, say, $75 per tonne. Deflated by a MCPF value of 1.5 that would result in a carbon tax of $50 per tonne, which equates to about 44 cents per gallon of gas (Lavelle 2019). A pre-tax price of $3.00 per gallon would imply the marginal social benefit of the fuel is nearly seven times the marginal social cost.

12.2.4 Tipping points

SCC calculations typically consider gradual impacts of a warming climate, such as slowly-melting glaciers and increasing average temperature. A driver of potentially high values of the Social Cost of Carbon (SCC) is the introduction into models of discrete catastrophic outcomes associated with abrupt changes (Dietz et al. 2021). They are often referred to as "tipping points."

The term "tipping point" mingles two different physical concepts that pose different research challenges. Many physical systems are inherently stable unless acted upon with sufficient external energy. For example an ice cap might remain intact over a wide range of temperatures but once the temperature crosses the 0°C threshold it melts. Such discontinuities are ubiquitous in nature and require an external force. Whether the force needs to be large relative to the size of the system depends on the underlying stability of the system.

A different type of tipping point is called a *bifurcation* and arises from the study of the internal dynamics of nonlinear systems (Crawford 1991). Many systems have been observed to have more than one equilibrium point and can move between them with minimal or no external influence. For example a weather system might have two different equilibrium states: one calm and one with a tornado. A transition from one to another can happen either with no external force or with a minuscule change, such as a flap of the proverbial butterfly's wings (Shen et al. 2014). The term "tipping point" is sometimes used to mean a bifurcation of this type and implies instability inherent in the system itself, which is not necessarily dependent on outside forces. It depends, instead, on parameters of the system taking values that support the emergence of bifurcations (Crawford 1991).

The two different concepts imply different research questions. Regarding the first we are interested in whether components of the climate system are susceptible to abrupt discontinuities in response to sufficiently-large anthropogenic forcing. Regarding the second we are interested in whether the Earth's climate system has inherent bifurcations that imply the possibility of abrupt transitions with or without external forcing.

Models have been developed that imply the latter is a possibility. Kypke et al. (2020) presented a simple climate model in which the GHG concentration is one of the parameters that controls the emergence of bifurcations of the Arctic climate to one with both cold and warm equilibria. If sufficiently high GHG forcing combined with a sufficiently high rate of ocean heat transport are

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imposed a bifurcation becomes possible. More generally GCMs have been observed to contain bifurcations and multiple equilibria (Brunetti and Ragon 2023).

The possible existence of bifurcations in the Earth's climate system implies abrupt transitions are possible, not just in response to large forcing but to small perturbations as well. This places tipping points into the category of low-likelihood and potentially catastrophic events, such as large meteor strikes. A key question to ask is whether those kinds of tipping points can be predicted. Current research has not resolved that question (Dakos et al 2024) and indeed may not be able to since one implication of the "butterfly effect" is the existence of predictability boundaries of nonlinear systems (Palmer et a. 2014). It is therefore not obvious how to incorporate such possibilities into SCC calculations. Small variations in assumptions will lead to arbitrarily large variations in the resulting SCC with no grounds for choosing among them. If such tipping points are possible the most appropriate stance for economic policy is to maximize resilience to any form of external catastrophe since it is unlikely we could predict or prevent it from happening.

The IPCC AR6 (Chapter 1) focuses mainly on the first type of tipping point, namely an abrupt change in response to external forcing. This is also the meaning associated with popular usage of the "tipping point" concept in discussions of climate change (see https://report-2023.global-tipping-points.org/what-is-a-tipping-point/ for example). As summarized by the IPCC AR6, there is evidence of abrupt change in the paleoclimate record, and some of these events have been interpreted as tipping points. Some projections with Earth System Models for example have produced tipping points such as Amazon forest dieback in response to specified values of CO_2 concentration or temperature increases.

The alarm surrounding climate tipping points is reflected by *The Global Tipping Points Report* that was launched at the COP28 on 6 December 2023 (Lenton et al., 2023). It identifies more than 25 parts of the climate system said to constitute tipping points. What gets classified as a climate "tipping point" is a moving target. The most common examples in the literature and assessment reports include: Greenland ice sheet disintegration, West Antarctic ice sheet disintegration, summertime disappearance of Arctic sea ice, Amazon rainforest dieback, coral reef dieoff, thawing of permafrost and methane hydrates, Atlantic Meridional Overturning Circulation collapse, boreal forest shift, West African monsoon shift, and Indian Monsoon shift.

All such tipping points require a certain amount of system instability in order to exhibit an abrupt transition in response to warming. For this reason there seems to be very little to discriminate between a tipping event and natural climate variability. Natural climate variability has in the past produced shifts in the West African and Indian monsoons, Amazon forest and coral reef dieback, and disintegration of the Greenland and West Antarctic ice sheets. These impacts can be reversed on the decadal timescales associated with natural climate variability and ecosystem responses.

Some abrupt changes are potentially more consequential, including collapse of the West Antarctic ice sheet and collapse of the Atlantic Meridional Overturning Circulation (AMOC). The IPCC AR6 WG1 Summary for Policy Makers states:

> "The Atlantic Meridional Overturning Circulation is very likely to weaken over the 21st century for all emission scenarios. While there is high confidence in the 21st century decline, there is only low confidence in the magnitude of the trend. There is medium confidence that there will not be an abrupt collapse before 2100." (C.3.4)

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"There is limited evidence for low-likelihood, high-impact outcomes (resulting from ice-sheet instability processes characterized by deep uncertainty and in some cases involving tipping points) that would strongly increase ice loss from the Antarctic Ice Sheet for centuries under high GHG emissions scenarios (e.g., SSP5-8.5)." (B.5.2)

For the purpose of SCC calculations the research question implied by this type of tipping point is whether such events have been observed in the past in climate conditions similar to what we currently experience or will in the near future. The IPCC AR6 finds little evidence for impending collapse of the Atlantic Meridional Overturning Circulation or the West Antarctic ice sheet. It finds there is no tipping point associated with Arctic Sea ice (AR6 Technical Summary p. 76)

Dietz et al. incorporated several potential tipping points (abrupt changes) into an SCC model and found they added about 25 percent to the estimate, mainly associated with thawing permafrost and release of methane hydrates. However the IPCC considers this scenario *very unlikely* (AR6 Technical Summary p. 107).

In summary, there may be unknown bifurcation tipping points that are associated with natural climate processes, but this possibility does not translate into specific guidance on the SCC. There are potential abrupt change points in the climate system in response to warming, although the IPCC assigns low probabilities to most, including the largest ones. When these have been taken into account the result is only a modest increase in the SCC value in the 21st century.

12.3 Summary

In summary, SCC estimates are highly uncertain due to unknowns in future economic growth, socioeconomic pathways, discount rates, climate damages, and system responses. The SCC is not intrinsically informative as to the economic or societal impacts of climate change. It provides an index connecting large networks of assumptions about the climate and the economy to a dollar value. Some assumptions yield a high SCC and others yield a low or negative SCC. The evidence for or against the underlying assumptions needs to be established independently; the resulting SCC adds no additional information about the validity of those assumptions.

It is increasingly being argued that the SCC is too variable to be useful for policymakers. Cambridge Econometrics (Thoung 2017) stated it's "time to kill it" due to uncertainties. The UK and EU no longer use SCC for policy appraisal, opting for "target-consistent" carbon pricing (UK Department for Energy Security and Net Zero 2022, Dunne 2017). However the weaknesses of the SCC concept don't mean that other regulatory measures are inherently better or more efficient. Many climate regulations (such as electric vehicle mandates, renewable energy mandates, energy efficiency regulations and bans on certain types of home appliances) end up costing far more per tonne of abatement than a simple price on carbon emissions.

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From: John Christy <climateman60@gmail.com>
Sent: Thursday, June 19, 2025 12:45 PM
To: Steven Koonin
Cc: Judith Curry; Roy W. Spencer; Ross McKitrick; Travis Fisher; Josh Loucks
Subject: Re: June 19, 2025: Propaganda only BBC can spew and pollute --- Three years left to limit warming to 1.5C, top scientists warn

Yes, the five of us against overwhelming numbers of the establishment. They don't address US climate and perhaps they don't say anything new. Let's all take a look.

John C.

Sent from my iPhone

On Jun 19, 2025, at 3:56 AM, Steven Koonin <steven.koonin@gmail.com> wrote:

Willie's right – we probably need to understand this, as it will be invoked to criticize CGA25 (paper attached)

SEK

From: Willie Soon <romeosoon@gmail.com>
Sent: Thursday, June 19, 2025 7:35 AM
To: Willie Soon <romeosoon@gmail.com>
Subject: June 19, 2025: Propaganda only BBC can spew and pollute --- Three years left to limit warming to 1.5C, top scientists warn

ps: here is the rapid publication of this pal-reviewed toilet paper by Piers Forster et al (June 19, 2025)

https://essd.copernicus.org/articles/17/2641/2025/essd-17-2641-2025-discussion.html

They can selectively ignore any and all published papers that are counter to their propaganda ... that is the only way for their voodoo science to survive

May I propose to all of you, in case you have not read yet, to read this new chapter we wrote for the Heritage Foundation?

https://report.heritage.org/sr305

or you want a shorter summary, study the two talks here:

https://www.ceres-science.com/post/ceres-at-the-heritage-foundation-symposium

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https://www.bbc.com/news/articles/cn4l927dj5zo

<image_2025-06-19_071200506.png>

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Sent from my iPhone
<essd-17-2641-2025.pdf>

DOJ_00000773

From: Steven Koonin [steven.koonin@gmail.com]
Sent: 6/19/2025 11:55:54 AM
To: 'John Christy' [climateman60@gmail.com]; 'Judith Curry' [curry.judith@gmail.com]; 'Roy W. Spencer' [roywspencer@hotmail.com]; 'Ross McKitrick' [ross.mckitrick@gmail.com]
CC: 'Travis Fisher' [travis.scott.fisher@gmail.com]; 'Josh Loucks' [loucksj14@gmail.com]
Subject: FW: June 19, 2025: Propaganda only BBC can spew and pollute --- Three years left to limit warming to 1.5C, top scientists warn
Attachments: image_2025-06-19_071200506.png; IMG_0222.jpg; essd-17-2641-2025.pdf

Willie's right – we probably need to understand this, as it will be invoked to criticize CGA25 (paper attached)

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https://essd.copernicus.org/articles/17/2641/2025/essd-17-2641-2025-discussion.html

They can selectively ignore any and all published papers that are counter to their propaganda … that is the only way for their voodoo science to survive

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https://report.heritage.org/sr305

or you want a shorter summary, study the two talks here:

https://www.ceres-science.com/post/ceres-at-the-heritage-foundation-symposium

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https://www.bbc.com/news/articles/cn4l927dj5zo

Three years left to limit warming to 1.5C, leading scientists warn

11 hours ago

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Mark Poynting
Climate reporter, BBC News

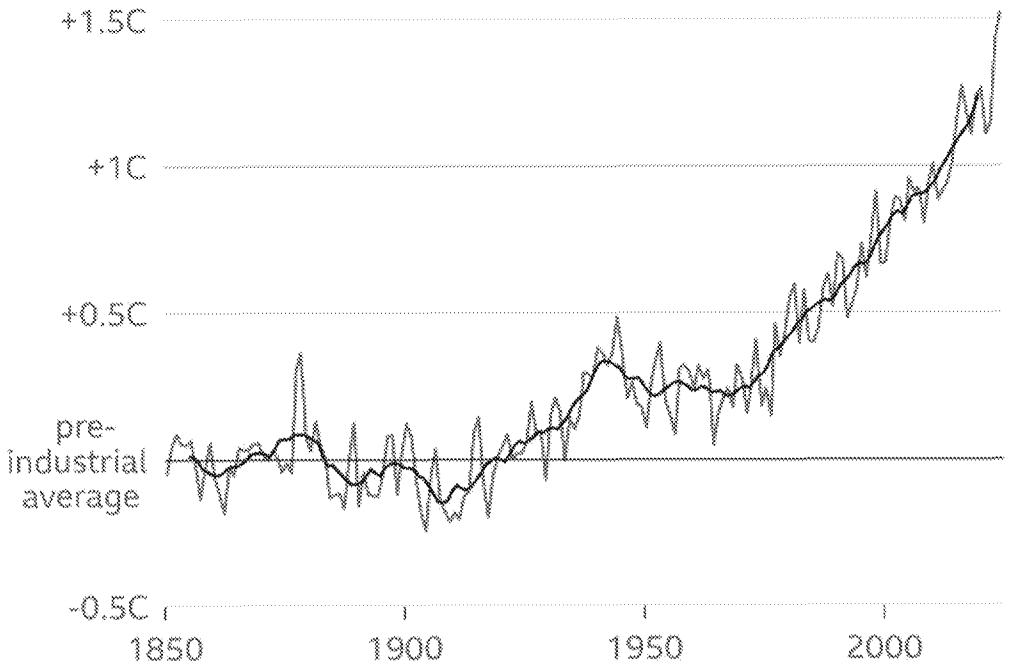
The Earth could be doomed to breach the symbolic 1.5C warming limit in as little as three years at current levels of carbon dioxide emissions.

That's the stark warning from more than 60 of the world's leading climate scientists in the most up-to-date assessment of the state of global warming.

Nearly 200 countries agreed to try to limit global temperature rises to 1.5C above levels of the late 1800s in a landmark agreement in 2015, with the aim of avoiding some of the worst impacts of climate change.

How the planet's temperature has risen

Global air temperature compared with pre-industrial (1850-1900) levels, as yearly average and **10-year average**



Temperatures calculated from average of four different global datasets

Source: Forster et al. (2025), Earth System Science Data

BBC

Sent from my iPhone

Earth Syst. Sci. Data, 17, 2641–2680, 2025
https://doi.org/10.5194/essd-17-2641-2025
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Open Access Earth System Science Data

Indicators of Global Climate Change 2024: annual update of key indicators of the state of the climate system and human influence

Piers M. Forster[1], Chris Smith[2,3], Tristram Walsh[4], William F. Lamb[1,5], Robin Lamboll[6], Christophe Cassou[7,8], Mathias Hauser[9], Zeke Hausfather[10,11], June-Yi Lee[12,13], Matthew D. Palmer[14,15], Karina von Schuckmann[16], Aimée B. A. Slangen[17], Sophie Szopa[18], Blair Trewin[19], Jeongeun Yun[12], Nathan P. Gillett[20], Stuart Jenkins[4], H. Damon Matthews[21], Krishnan Raghavan[22], Aurélien Ribes[23], Joeri Rogelj[3,6,24], Debbie Rosen[1], Xuebin Zhang[25], Myles Allen[4,26], Lara Aleluia Reis[27,28], Robbie M. Andrew[29], Richard A. Betts[14,30], Alex Borger[31], Jiddu A. Broersma[31], Samantha N. Burgess[32], Lijing Cheng[33], Pierre Friedlingstein[7,30], Catia M. Domingues[34,35], Marco Gambarini[27,28], Thomas Gasser[3], Johannes Gütschow[36], Masayoshi Ishii[37], Christopher Kadow[38], John Kennedy[39], Rachel E. Killick[14], Paul B. Krummel[40], Aurélien Liné[8,16,41], Didier P. Monselesan[42], Colin Morice[14], Jens Mühle[43], Vaishali Naik[44], Glen P. Peters[29], Anna Pirani[45], Julia Pongratz[46,47], Jan C. Minx[1,5], Matthew Rigby[48], Robert Rohde[10], Abhishek Savita[49,50], Sonia I. Seneviratne[9], Peter Thorne[51], Christopher Wells[1], Luke M. Western[48], Guido R. van der Werf[52], Susan E. Wijffels[42,53], Valérie Masson-Delmotte[18], and Panmao Zhai[54]

[1]Priestley Centre for Climate Futures, University of Leeds, Leeds, LS2 9JT, UK
[2]Department of Water and Climate, Vrije Universiteit Brussel, Brussels, Belgium
[3]International Institute for Applied Systems Analysis (IIASA), Vienna, Austria
[4]Environmental Change Institute, University of Oxford, Oxford, UK
[5]Potsdam Institute for Climate Impact Research (PIK), Member of the Leibniz Association, Potsdam, Germany
[6]Centre for Environmental Policy, Imperial College London, London, UK
[7]Laboratoire de Météorologie Dynamique/Institut Pierre-Simon Laplace, CNRS, Ecole Normale Supérieure/Université PSL, Paris, France
[8]CECI, Université de Toulouse, CERFACS, CNRS, Toulouse, France
[9]Institute for Atmospheric and Climate Science, Department of Environmental Systems Science, ETH Zurich, Zurich, Switzerland
[10]Berkeley Earth, Berkeley, CA, USA
[11]Stripe Inc., South San Francisco, CA, USA
[12]Research Center for Climate Sciences, Pusan National University, Busan, Republic of Korea
[13]Center for Climate Physics, Institute for Basic Science, Busan, Republic of Korea
[14]Met Office Hadley Centre, Exeter, UK
[15]School of Earth Sciences, University of Bristol, Bristol, UK
[16]Mercator Ocean international, Toulouse, France
[17]NIOZ Royal Netherlands Institute for Sea Research, Department of Estuarine and Delta Systems, Yerseke, the Netherlands
[18]Institut Pierre Simon Laplace, Laboratoire des Sciences du Climat et de l'Environnement (UMR 8212 CEA-CNRS-UVSQ), Université Paris-Saclay, Gif-sur-Yvette, France
[19]Bureau of Meteorology, Melbourne, Australia
[20]Canadian Centre for Climate Modelling and Analysis, Environment and Climate Change Canada, Victoria, BC, Canada
[21]Department of Geography, Planning and Environment, Concordia University, Montreal, Canada
[22]Indian Institute of Tropical Meteorology, Pune, India
[23]CNRM, Université de Toulouse, Météo France, CNRS, Toulouse, France

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[24]Grantham Institute for Climate Change and Environment, Imperial College London, United Kingdom
[25]Pacific Climate Impacts Consortium, University of Victoria, Victoria, Canada
[26]Atmospheric, Oceanic and Planetary Physics, Department of Physics, University of Oxford, Oxford, UK
[27]CMCC Foundation, Euro-Mediterranean Center on Climate Change, Lecce, Italy
[28]RFF-CMCC, European Institute on Economics and the Environment, Milan, Italy
[29]CICERO Center for International Climate Research, Oslo, Norway
[30]Global Systems Institute, Science and Economy, University of Exeter, Exeter, UK
[31]Climate Change Tracker, Data for Action Foundation, Amsterdam, the Netherlands
[32]European Centre for Medium-Range Weather Forecasts, ECWMF, Reading, United Kingdom
[33]State Key Laboratory of Earth System Numerical Modeling and Application, Institute of Atmospheric Physics, Chinese Academy of Sciences, Beijing, China
[34]Marine Physics and Ocean Climate, National Oceanography Centre, Southampton, UK
[35]Environmental Business Unit, CSIRO, Hobart, Tasmania, Australia
[36]Climate Resource, Melbourne, Australia
[37]Meteorological Research Institute, Tsukuba, Japan
[38]German Climate Computing Center (DKRZ), Hamburg, Germany
[39]independent researcher: Verdun, France
[40]CSIRO Environment, Aspendale, Australia
[41]Institut de Mécanique des Fluides de Toulouse, Université de Toulouse, INP, CNRS, Toulouse, France
[42]CSIRO, Environment Research Unit, Climate intelligence, climate variability and hazards, Hobart, Tasmania, Australia
[43]Scripps Institution of Oceanography, University of California San Diego, La Jolla, CA, USA
[44]NOAA Geophysical Fluid Dynamics Laboratory, Princeton, NJ, USA
[45]Euro-Mediterranean Center on Climate Change (CMCC), Venice, Italy
[46]Ludwig-Maximilians-Universität München, Munich, Germany
[47]Max Planck Institute for Meteorology, Hamburg, Germany
[48]School of Chemistry, University of Bristol, Bristol, United Kingdom
[49]Centre for Atmospheric Sciences, Indian Institute of Technology Delhi, Delhi, India
[50]Department of Atmospheric Sciences, Rosenstiel School of Marine, Atmospheric and Earth Science, Miami, FL, USA
[51]ICARUS Climate Research Centre, Maynooth University, Maynooth, Ireland
[52]Wageningen University and Research, Wageningen, the Netherlands
[53]Physical Oceanography, Woods Hole Oceanographic Institution, Woods Hole, MA, USA
[54]Chinese Academy of Meteorological Sciences, Beijing, China
Correspondence: Piers M. Forster (p.m.forster@leeds.ac.uk)

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Abstract. In a rapidly changing climate, evidence-based decision-making benefits from up-to-date and timely information. Here we compile monitoring datasets (published at https://doi.org/10.5281/zenodo.15639576; Smith et al., 2025a) to produce updated estimates for key indicators of the state of the climate system: net emissions of greenhouse gases and short-lived climate forcers, greenhouse gas concentrations, radiative forcing, the Earth's energy imbalance, surface temperature changes, warming attributed to human activities, the remaining carbon budget, and estimates of global temperature extremes. This year, we additionally include indicators for sea-level rise and land precipitation change. We follow methods as closely as possible to those used in the IPCC Sixth Assessment Report (AR6) Working Group One report.

The indicators show that human activities are increasing the Earth's energy imbalance and driving faster sea-level rise compared to the AR6 assessment. For the 2015–2024 decade average, observed warming relative to 1850–1900 was 1.24 [1.11 to 1.35] °C, of which 1.22 [1.0 to 1.5] °C was human-induced. The 2024-observed best estimate of global surface temperature (1.52 °C) is well above the best estimate of human-caused warming (1.36 °C). However, the 2024 observed warming can still be regarded as a typical year, considering the human-induced warming level and the state of internal variability associated with the phase of El Niño and Atlantic variability. Human-induced warming has been increasing at a rate that is unprecedented in the instrumental record, reaching 0.27 [0.2–0.4] °C per decade over 2015–2024. This high rate of warming is caused by a combination of greenhouse gas emissions being at an all-time high of $53.6 \pm 5.2\,\mathrm{Gt\,CO_2e\,yr^{-1}}$ over the last decade

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(2014–2023), as well as reductions in the strength of aerosol cooling. Despite this, there is evidence that the rate of increase in CO_2 emissions over the last decade has slowed compared to the 2000s, and depending on societal choices, a continued series of these annual updates over the critical 2020s decade could track decreases or increases in the rate of the climatic changes presented here.

1 Introduction

IPCC AR6 provided an assessment of human influence on key indicators of the state of the climate grounded in available data at the time of publication. The preparation for the next IPCC report, the Seventh Assessment Report (AR7), has started, and the assessment is due in around 5 years. Given the speed of recent change, and the need for updated climate knowledge to inform evidence-based decision-making, the Indicators of Global Climate Change (IGCC) was initiated to provide policymakers with annual updates of the latest scientific understanding on the state of selected critical indicators of the climate system and where possible of the quantified human influence upon these.

IGCC complements other annual updates, most notably the BAMS State of the Climate Report (Dunn et al., 2024) and the WMO State of the Global Climate (WMO, 2025). The main difference is that this work goes beyond the observations to make process-level estimates of effective radiative forcing and attributed human-induced response using methods rigorously assessed in AR6.

This third annual update follows broadly the format of last year (Forster et al., 2024), which extended indicators through 2023. The work focuses on indicators related to heating of the climate system, building from greenhouse gas emissions towards estimates of human-induced warming and the remaining carbon budget for 1.5 °C and other policy-relevant temperature thresholds. Figure 1 presents an overview of the aspects assessed and their interlinkages from cause (emissions) through effect (changes in physical indicators) to climatic impact drivers. It also provides a visual roadmap as to the structure of remaining sections in this paper to guide the reader.

The update is based on methodologies assessed by the IPCC Sixth Assessment Report (AR6) of the physical science basis of climate change (Working Group One (WGI) report; IPCC, 2021a) as well as Chap. 2 of the WGIII report (Dhakal et al., 2022) and is aligned with the efforts initiated in AR6 to implement FAIR (Findable, Accessible, Interoperable, Reusable) principles for reproducibility and reusability (Pirani et al., 2022; Iturbide et al., 2022). IPCC reports make a much wider assessment of the science and methodologies – we do not attempt to reproduce the comprehensive nature of these IPCC assessments here. We also do not consider adopting fundamentally different approaches to AR6. Rather, our aim is to rigorously track both climate system change and evolving methodological improvements between IPCC report cycles, thereby increasing transparency and consistency in between successive reports.

This annual update is organised as follows: greenhouse gas (GHG) emissions (Sect. 2), greenhouse gas concentrations (Sect. 3) and emissions of short-lived climate forcers (SLCFs) (Sect. 4) are used to develop updated estimates of effective radiative forcing (Sect. 5). The Earth energy imbalance (Sect. 6) and observations of global surface temperature change (Sect. 7) are key global indicators of a warming world. The contributions to global surface temperature change from human and natural influences are formally attributed in Sect. 8, which tracks the level and rate of human-induced warming. Section 9 updates the remaining carbon budget for policy-relevant temperature thresholds. Section 10 gives an example of global-scale indicators associated with climate extremes of maximum land surface temperatures, and Sect. 11 shows land surface precipitation trends traceable to AR6, a new addition to this year's update. Section 12 presents updated estimates of global mean sea-level rise, also a new addition. Code and data availability is given in Sect. 13, and conclusions are presented in Sect. 14. Data are available at https://doi.org/10.5281/zenodo.15639576 (Smith et al., 2025a).

2 Greenhouse gas emissions

Historic GHG emissions from human activity were assessed in both AR6 WGI and WGIII. Chapter 5 of WGI assessed CO_2 and CH_4 emissions in the context of the carbon cycle (Canadell et al., 2021). Chapter 2 of WGIII, published 1 year later (Dhakal et al., 2022), assessed the sectoral sources of emissions and gave the most up-to-date understanding of the current level of emissions. This section bases its methods and data on those employed in this WGIII chapter.

2.1 Methods of estimating greenhouse gas emissions changes

Like in AR6 WGIII, net GHG emissions in this paper refer to releases of GHGs from anthropogenic sources minus removals by anthropogenic sinks, for the set of GHGs outlined in the United Nations Framework Convention on Climate Change (UNFCCC). These include CO_2 emissions from fossil fuels and industry (CO_2-FFI); net CO_2 emissions from land use, land-use change and forestry (CO_2-LULUCF); CH_4 emissions; N_2O emissions; and fluorinated gas (F-gas) emissions comprising hydrofluorocarbons (HFCs), perfluo-

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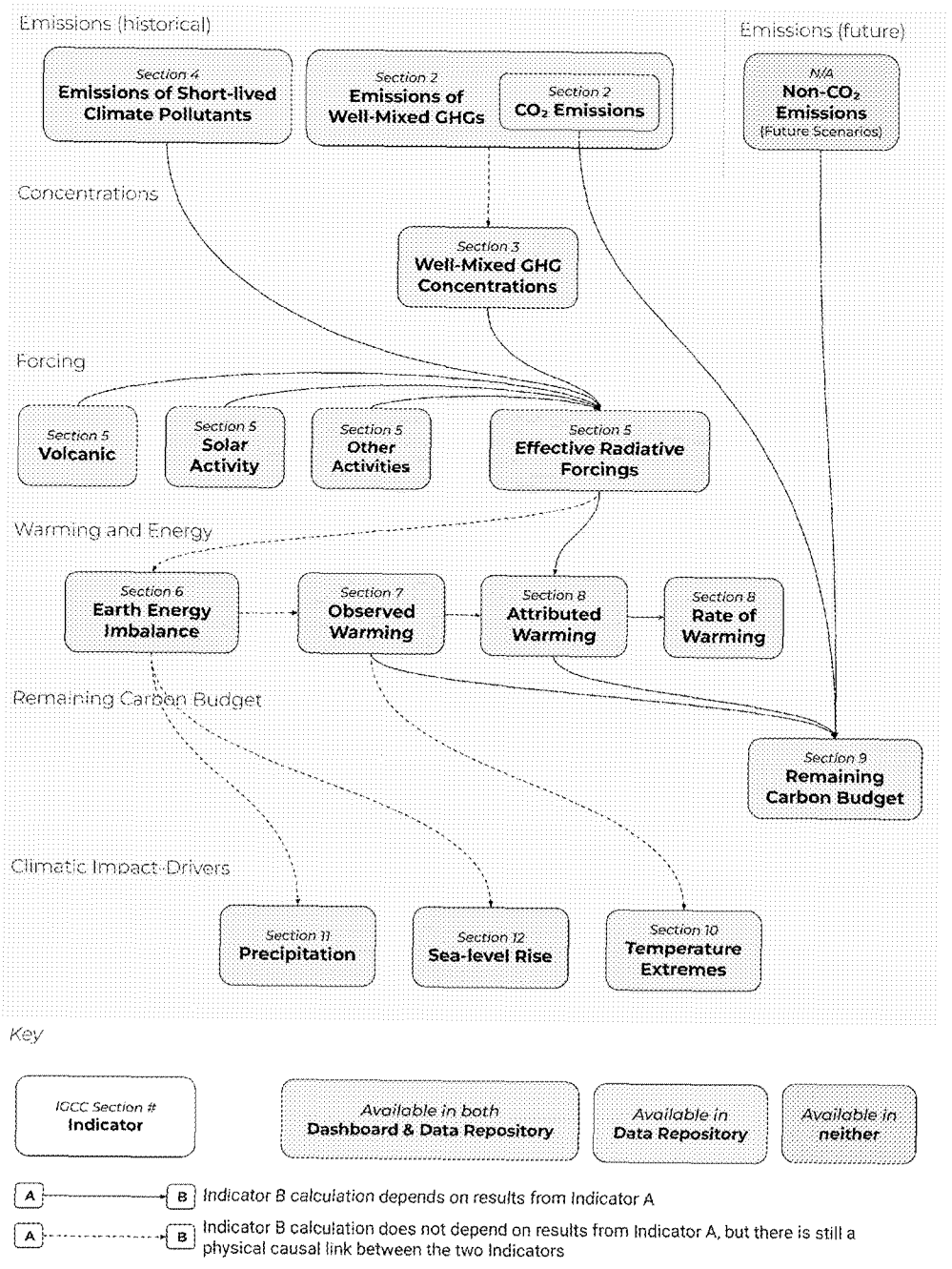

Figure 1. The flow chart of data production from emissions to human-induced warming, the remaining carbon budget and changes to climatic impact drivers, illustrating both the rationale and workflow within the paper production.

rocarbons (PFCs), sulfur hexafluoride (SF_6) and nitrogen trifluoride (NF_3) – hereafter the "UNFCCC F-gases".

Despite extensive literature on GHG emissions, there remains important differences in reporting conventions and system boundaries between assessments. These differences relate to three underlying issues: (1) emissions datasets vary in their coverage of sources and sectors; (2) there are different approaches to determining the "anthropogenic" component of LULUCF emissions and removals; and (3) the Paris Agreement does not cover all relevant sources of emissions (Lamb et al., 2025).

Concerning the first issue, there are several possible emissions datasets to draw from, each with varying coverage and update schedules. Emissions data are gathered by countries and submitted to the UNFCCC in the form of national inventory reports and common reporting tables. However, these "national inventories" are generally incomplete and are not kept up to date for all countries. Emissions re-

DOJ 00000780

porting therefore often relies on "third-party" datasets compiled by research organisations, including the Global Carbon Budget (GCB; Friedlingstein et al., 2025), the Emissions Database for Global Atmospheric Research (EDGAR; Crippa et al., 2023), the Potsdam Real-time Integrated Model for probabilistic Assessment of emissions Paths (PRIMAP-hist; Gütschow et al., 2016, 2025)[1], the Community Emissions Data System (CEDS; Hoesly et al., 2018; Hoesly and Smith, 2024) and the Global Fire Emissions Database (GFED; van der Werf et al., 2017). As detailed below, for various reasons not all these datasets were employed in this update.

Concerning the second issue, there are varying conventions used to quantify CO_2-LULUCF fluxes. These include the use of bookkeeping models and aggregated national inventory reporting (Pongratz et al., 2021), which differ in terms of their applied system boundaries and definitions and in particular how they treat "indirect anthropogenic effects" such as the influence of increased atmospheric CO_2 on vegetation growth. As such, the CO_2-LULUCF emissions estimates generated using bookkeeping models versus national inventories are not directly comparable and differ by about 7.5 Gt CO_2 yr^{-1} (2013–2022 average), but there are now methods to "translate" between these two approaches (Friedlingstein et al., 2022; Grassi et al., 2023; Schwingshackl et al., 2022). Assessments also differ with respect to biomass fire emissions and to what extent components of these are treated as anthropogenic (Lamb et al., 2025).

Finally, two categories of emissions are not directly covered by the Paris Agreement but might be considered depending on the objectives of an assessment. These include the ozone-depleting substances (hereafter the "ODS F-gases") comprising halons, chlorofluorocarbons (CFCs) and hydrochlorofluorocarbons (HCFCs). The ODS F-gases were initially controlled under the Montreal Protocol, and its amendments and are therefore not included in national inventories submitted to the UNFCCC, nor in many third-party emissions datasets – in contrast to the UNFCCC F-gases. Another important omission is the cement carbonation sink. To date this has also been excluded from national reporting under the UNFCCC, but plans for a new chapter covering these removals in the IPCC Task Force on National Greenhouse Gas Inventory Guidelines indicate a pathway for its eventual inclusion (IPCC, 2025).

The IPCC AR6 WGIII addressed these issues as follows. Total net GHG emissions were calculated as the sum of CO_2-FFI, CH_4, N_2O and UNFCCC F-gases from EDGAR (version 6, with a fast-track methodology applied for the final year of data – 2019) and net CO_2-LULUCF emissions from the GCB (the 2020 version; Friedlingstein et al., 2020). Net CO_2-LULUCF emissions followed the GCB convention and were derived from the average of three bookkeeping models (Hansis et al., 2015; Houghton and Nassikas, 2017; Gasser et al., 2020). "Indirect anthropogenic effects" on the terrestrial carbon fluxes were therefore excluded from totals (i.e. they were treated as part of the natural land sink). Further, the GCB methodology (and thus reporting in IPCC AR6 WGIII) includes CO_2 emissions from deforestation and forest degradation fires but excludes those from wildfires, which are classified as natural even if climate change affects their intensity and frequency. Similarly, the EDGAR dataset used in AR6 includes some non-CO_2 biomass fire emissions in the agricultural sector but otherwise excludes those from wildfires. Sources not covered by inventories or the Paris Agreement (ODS F-gases and cement carbonation) were also excluded. Together these choices ensured consistency with the Integrated Assessment Model (IAM) benchmarks reported in WGIII and were closely focused on direct anthropogenic emissions under the UNFCCC, reflecting the importance of human-driven technology and policy options in shaping the future climate response.

The analysis presented here continues to provide an "WGIII update" estimate that tracks the same system boundary and compilation of GHGs as in AR6 WGIII, albeit with some differences in the selected data sources. As in previous years, we use GCB data for CO_2-FFI. We also continue to use GCB for CO_2-LULUCF, which has now been updated to use the average of four (rather than three) bookkeeping models (BLUE by Hansis et al., 2015; H&C by Houghton and Castanho, 2023; OSCAR by Gasser et al., 2020; LUCE by Qin et al., 2024). We use PRIMAP Hist-TP data for CH_4 and N_2O and inversions of atmospheric concentrations tracked by NOAA and AGAGE with best-estimate lifetimes for UNFCCC F-gas emissions based on analysis in the subsequent section (Sect. 3) (Lan et al., 2025; Dutton et al., 2024; Prinn et al., 2018). We follow the same approach for estimating uncertainties and CO_2-equivalent (CO_2-e) emissions as in AR6, as described in the Supplement.

In addition to the WGIII update, we provide two further estimates that provide clarity and comparison to other assessment approaches. This reflects the fact that other decision criteria for tracking emissions are possible. First, in cases where assessments prioritise calculating the best estimate of fluxes to the atmosphere, it would be important to include ODS F-gases, cement carbonation and all non-CO_2 biomass fire emissions, including those from wildfires. Indeed, these are included in this article in subsequent assessments of concentration change (including compounds formed in the atmosphere as ozone), effective radiative forcing, human-induced warming, carbon budgets and climate impacts, in line with the WGI assessment. We therefore provide an "IPCC update + additional sources and sinks" estimate that shows the change implied by including these three components in the global total. Second, the IPCC AR7 report outline foresees the tracking of "inventory-aligned" emissions that are

[1]PRIMAP is a synthetic dataset that includes two time series: PRIMAP Hist-TP, which is compiled from other underlying products such as EDGAR, and PRIMAP Hist-CR, which prioritises data from national inventories but gap-fills these where necessary.

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consistent with national reporting. Full alignment between emissions inventories and WGIII emissions consistent with IAM benchmarks is essential for an accurate assessment and stocktake of the nationally determined contributions (NDCs) and pathways to net-zero emissions (Grassi et al., 2021; Gidden et al., 2023; Allen et al., 2025). We therefore provide an inventory-aligned estimate that follows the inventory approach to accounting for LULUCF emissions, while also integrating the latest national inventory data from the Common Reporting Tables. The data sources associated with these additional estimates are detailed in Table S1 in the Supplement.

We expect to see differences between the three estimates, most notably between the WGIII update and inventory-aligned estimates. As discussed above, these differ conceptually in their treatment of the LULUCF sector. However, national inventory reporting can also differ from third-party datasets in terms of underlying methods: in some countries, investments into statistical infrastructures have enabled the use of more precise emissions factors in inventories to estimate fluxes according to local or national conditions, while in others this may not be the case. In contrast, third-party datasets often use globally consistent emissions factors. Notably, the PRIMAP Hist-CR dataset, which is used here to represent national inventories, has significantly lower total CH_4 emissions relative to other datasets reported here, as well as the global atmospheric inversion estimates evaluated in this paper. A substantive body of literature has found that, on average, national inventories tend to underestimate CH_4 compared to inversions (Deng et al., 2022; Tibrewal et al., 2024; Janardanan et al., 2024; Scarpelli et al., 2022).

2.2 Updated greenhouse gas emissions

Updated GHG emission estimates following the WGIII assessment are presented in Fig. 2 and Table 1. Total global GHG emissions were $55.4 \pm 5.1\,\mathrm{Gt\,CO_2e}$ in 2023. Of this total, CO_2-FFI contributed $37.8 \pm 3.0\,\mathrm{Gt\,CO_2}$, CO_2-LULUCF contributed $3.6 \pm 2.5\,\mathrm{Gt\,CO_2}$, CH_4 contributed $9.2 \pm 2.7\,\mathrm{Gt\,CO_2e}$, N_2O contributed $2.9 \pm 1.7\,\mathrm{Gt\,CO_2e}$ and F-gas emissions contributed $1.9 \pm 0.6\,\mathrm{Gt\,CO_2e}$.

Note the recent history of emissions in these datasets is continually revised, so there are small differences between each annual update in emission estimates over the recent past. Initial projections for 2024 indicate that CO_2 emissions from fossil fuels and industry increased to 38.2 ± 3.0, and CO_2 emissions from land-use change increased to $4.2 \pm 2.8\,\mathrm{Gt\,CO_2}$ (Friedlingstein et al., 2025; Deng et al., 2025). The significant increase in land-use change emissions is connected to high emissions from tropical deforestation and degradation fires in the aftermath of the El Niño with droughts in South America continuing since 2023. Synchronous large fires occurred in North America, where the record-breaking Canadian fires of 2023 were followed by another year that was well above average in 2024 but are attributable to climate variability and climate change and not anthropogenic land-use change (Friedlingstein et al., 2025).

Average annual GHG emissions for the decade 2014–2023 were $53.6 \pm 5.2\,\mathrm{Gt\,CO_2e}$. Average decadal GHG emissions have increased steadily since the 1970s across all major groups of GHGs, driven primarily by increasing CO_2 emissions from fossil fuel and industry but also rising emissions of CH_4 and N_2O. Emissions of UNFCCC F-gases have grown more rapidly than other GHG but from low levels. Both the magnitude and trend of CO_2 emissions from land-use change remain highly uncertain, with the latest data indicating an average net flux between 4–5 $\mathrm{Gt\,CO_2\,yr^{-1}}$ for the past few decades.

The fossil fuel share of global GHG emissions was approximately 70 % in 2023 (GWP100 weighted), based on the EDGAR v9 dataset (Crippa et al., 2023) and net land-use CO_2 emissions from the Global Carbon Budget (Friedlingstein et al., 2025). The remaining share of non-fossil fuel emissions is mostly from land-use change, agriculture, cement production, waste and F-gas emissions.

Different emissions assessment approaches are shown in Fig. 3. Increasing the scope of the WGIII update to include ODS F-gases, cement carbonation, and CH_4 and N_2O from biomass burning results in emissions of $56.9 \pm 5.2\,\mathrm{Gt\,CO_2e\,yr^{-1}}$ in 2023 or a total change of $+1.6\,\mathrm{Gt\,CO_2e\,yr^{-1}}$. ODS F-gas emissions have declined substantially since the 1990s under the Montreal Protocol and its amendments, reaching $1.3\,\mathrm{Gt\,CO_2e\,yr^{-1}}$ in 2023, with a stalling rate of reduction in the past decade. The cement carbonation sink has steadily increased alongside cement production to reach $-0.8\,\mathrm{Gt\,CO_2e\,yr^{-1}}$ in 2023. Biomass fire emissions have a more variable trend, and 2023 was a relatively extreme year at $1\,\mathrm{Gt\,CO_2e\,yr^{-1}}$, compared to an average of $0.7\,\mathrm{Gt\,CO_2e\,yr^{-1}}$ in the preceding decade.

Emissions according to national inventories were $47.1 \pm 4.7\,\mathrm{Gt\,CO_2e\,yr^{-1}}$ in 2023 or $8.3\,\mathrm{Gt\,CO_2e\,yr^{-1}}$ lower than the WGIII update (Fig. 3). The main reason is diverging estimates of net LULUCF emissions, which according to inventory accounts were on average $7.5\,\mathrm{Gt\,CO_2}$ lower over the past decade (2014–2023). Additional differences result from a lower estimate of energy, industrial process, agriculture and waste emissions in inventories ($-1.8\,\mathrm{Gt\,CO_2e\,yr^{-1}}$), particularly for CH_4 ($-0.7\,\mathrm{Gt\,CO_2e\,yr^{-1}}$).

Emerging literature, published after AR6, suggests that increases in atmospheric CH_4 concentrations may also be driven by methane emissions from wetland changes resulting from climate change and variability (e.g. Basu et al., 2022; Hardy et al., 2023; Peng et al., 2022; Nisbet et al., 2023; Zhang et al., 2023). There is also a possible effect from CO_2 fertilisation (Feron et al., 2024; Hu et al., 2023). The latest global methane budget estimates indirect anthropogenic CH_4 fluxes from wetlands and freshwater bodies of approximately $2.4\,\mathrm{Gt\,CO_2e\,yr^{-1}}$ (Saunois et al., 2025). Such emissions are not captured in the WGIII estimate here as they are not a direct emission from human activity but rather a feedback

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induced by a changing climate, yet they will contribute to GHG concentration rise, forcing and energy budget changes discussed in the next sections. They will become more important to properly account for in future years. Note that these indirect CH_4 emissions are not used to determine the effective radiative forcing in Sect. 5.

3 Well-mixed greenhouse gas concentrations

As in Forster et al. (2024), we report best-estimate global mean concentrations for 52 well-mixed GHGs. These concentrations are updated to 2024. CO_2 mixing ratios were taken from the NOAA Global Monitoring Laboratory (GML) and are updated here through 2024 (Lan et al., 2025). As in Forster et al. (2023, 2024), CO_2 is reported on the WMO-CO_2-X2019 scale, which differs from the WMO-CO_2-X2007 scale used in AR6, with WMO-CO_2-X2019 being around 0.18 ppm higher than WMO-CO_2-X2007 in recent years. For consistency with WMO-CO_2-X2019, the AR6 CO_2 concentrations that make up the 1750 to 1978 period in the IGCC dataset (before recent NOAA updates) have been converted to the WMO-CO_2-X2019 scale. Other GHG records were compiled from NOAA and AGAGE global networks or extrapolated from the literature. Average NOAA and AGAGE data, updated through 2024, were used for N_2O, CH_4, CFC-11, CFC-12, CCl_4, HCFC-22, HFC-134a and HFC-125 (Lan et al., 2025; Dutton et al., 2024; Prinn et al., 2018), which, along with CO_2, account for over 97 % of the effective radiative forcing (ERF) from well-mixed GHGs. Several other species also use means from the NOAA and AGAGE networks, where the NOAA data are updated to 2024 from the values given in the BAMS State of the Climate Report (Dunn et al., 2024), and AGAGE data up until 2022 are available; for 2023 and 2024, an offset to the NOAA data was applied, which was equal to the mean difference between the NOAA and AGAGE datasets over the recent past. In cases where no updated information is available, global estimates were extrapolated from Vimont et al. (2022), Western et al. (2023, 2024), or other literature and scaled to be consistent with those reported in AR6. Some extrapolations are based on data from the mid-2010s (Droste et al., 2020; Laube et al., 2014; Simmonds et al., 2017; Vollmer et al., 2018) but have an imperceptible effect on the total ERF assessed in Sect. 5 and are included to maintain consistency with AR6. Mixing ratio uncertainties for 2024 are assumed to be like 2019, and we adopt the same uncertainties as assessed in AR6 WGI.

Figure 4 shows recent GHG concentrations and their changes. Table S2 in the Supplement shows specific updated concentrations for all the GHGs considered. The global surface mean concentrations of CO_2, CH_4 and N_2O in 2024 were 422.8 [±0.4] ppm (parts per million), 1929.7 [±3.3] ppb (parts per billion) and 337.9 [±0.4] ppb, respectively. Concentrations of all three major GHGs have increased since 2019, with CO_2 increasing by 12.7 ppm, CH_4 by 63.3 ppb and N_2O by 5.8 ppb. Increases since 2019 are consistent with those from the CSIRO network (Francey et al., 1999), which are 13.0 ppm, 61.9 ppb and 6.0 ppb for CO_2, CH_4 and N_2O, respectively. With few exceptions, concentrations of ozone-depleting substances, such as CFC-11 and CFC-12, continue to decline, while those of replacement compounds (HFCs) have increased. HFC-134a, for example, has increased 25 % since 2019 from 107.6 to 134.7 ppt (parts per trillion). Aggregated across all gases, PFCs increased from 109.7 to an estimated 117.4 ppt CF_4-e from 2019 to 2024 and HFCs from 237 to 3212 ppt HFC-134a-e, while ozone-depleting gases declined from 1032 to 995 ppt CFC-12-e. Mixing ratio equivalents are determined by the radiative efficiencies of each GHG from Hodnebrog et al. (2020).

Ozone and other non-methane SLCFs are not well mixed in the atmosphere and are thus discussed separately (in Sect. 4). For this reason, the warming impact of ozone, the third-most-important GHG (in terms of current contribution to warming), is not included in the contribution of well-mixed GHGs to observed warming, consistently with AR6. Note that change in methane concentration affects ozone, but this indirect effect is not accounted for in the estimate of the warming due to the evolution of well-mixed GHG concentrations.

4 Non-methane short-lived climate forcers

Chapter 6 of WGI assessed emissions in the context of understanding the climate and air quality impacts of SLCFs (Szopa et al., 2021). Methane is a SLCF but also a well-mixed GHG and is discussed in Sects. 2 and 3. Trends in SLCFs emissions are spatially heterogeneous (Szopa et al., 2021), with strong shifts in the locations of reductions and increases over the decade 2010–2019 (Hodnebrog et al., 2024). Concentrations of non-methane SLCFs are heterogeneously distributed in the atmosphere, and the observation networks are too sparse to report globally averaged concentrations. Typically, a combination of satellite data, where available, and global models and reanalysis is relied upon for producing global-scale distributions. In the case of models, production of near-real-time information relies upon the availability of near-real-time updates to SLCF emissions which are still challenging. Little information, whether from observations from local monitoring networks, from satellite data or from global model reanalysis, is released in near-real time.

In addition to GHG emissions, we provide an update of anthropogenic emissions of non-methane SLCFs (SO_2, black carbon (BC), organic carbon (OC), NO_x, volatile organic compounds (VOCs), CO and NH_3). Data are presented in Table 2, and the evolution of SLCF emission estimates from the AR6 to this study is presented in Sect. S4 of the Supplement. Consistency between emission trends and concentra-

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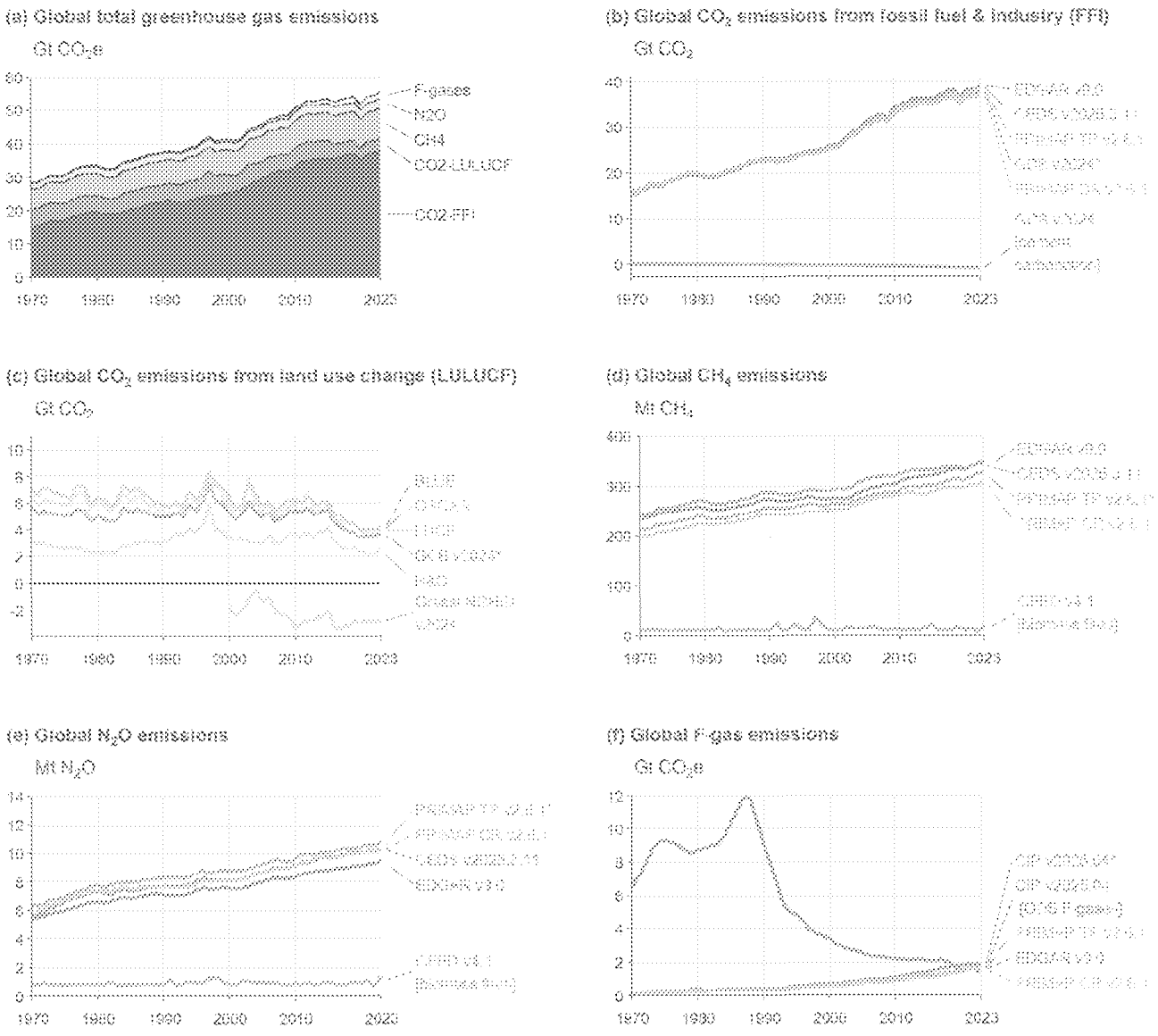

Figure 2. Annual global anthropogenic GHG emissions by source, 1970–2023. Refer to Sect. 2.1 and Table S1 for a list of datasets. Datasets with an asterisk (*) indicate the sources used to compile global total greenhouse gas emissions following the WGIII assessment in **(a)**. CO_2-equivalent emissions in **(a)** and **(f)** are calculated using GWP100 from the AR6 WGI Chap. 7 (Forster et al., 2021). F-gas emissions in **(a)** comprise only UNFCCC F-gas emissions (see Sect. 2.1 for a list of species). F-gas emissions in **(f)** refer to UNFCCC F-gases, except for "CIP v2024.04 [ODS F-gases]". Some of the major depicted differences between datasets (e.g. between GCB v2024 and Grassi NGHGI v2024 in panel **c**) are due to varying system boundaries, rather than underlying uncertainties in activity levels or emissions factors.

tions is considered whenever feasible. HFCs, whatever their lifetimes, were considered in Sect. 2.2.

Sectoral emissions of SLCFs are derived from two sources: CEDS, which was used in the AR6 and in CMIP6 to assess historical evolution of atmospheric composition and that has been updated since then, and the Copernicus Atmosphere Monitoring Service (CAMS). The most recent release of the CEDS anthropogenic emissions dataset (Hoesly et al., 2025) covers the 1750–2023 period (Hoesly et al., 2018; Hoesly and Smith, 2024). Since 2023, CAMS has released regular updates of their global emission dataset (Soulie et al., 2024). For the year 2024, we apply, for each compound, the trend in emission from the CAMS dataset to the 2023 CEDS emission. The CAMS dataset is essentially based on the EDGARv6/v7 emissions as well as on CEDS, so CEDS and CAMS are not entirely independent. The temporal extension is based on evolution of drivers of emissions (energy consumption, production rates) and trends in technologies that affect the emissions factors (e.g. fleet renewal and abatement systems) (Denier van der Gon et al., 2023).

The CAMS v6.2 emission dataset (ECCAD, 2025) indicates a decrease in global anthropogenic emissions of the

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Table 1. Global anthropogenic greenhouse gas emissions by source and decade following the WGIII assessment. All numbers refer to decadal averages, except for annual estimates in 2023 and 2024. CO_2-equivalent emissions are calculated using GWP100 from AR6 WGI Chap. 7 (Forster et al., 2021). Projections of non-CO_2 GHG emissions in 2024 remain unavailable at the time of publication. Uncertainties are ±8 % for CO_2-FFI, ±70 % for CO_2-LULUCF, ±30 % for CH_4 and F-gases, and ±60 % for N_2O, corresponding to a 90 % confidence interval. "GHG" in row one is the sum of the other rows.

Units: Gt CO_2e	1970–1979	1980–1989	1990–1999	2000–2009	2010–2019	2014–2023	2023	2024 (projection)
GHG	30.9 ± 4.5	34.6 ± 4.6	39.3 ± 5.1	45.1 ± 5.1	52.9 ± 5.4	53.6 ± 5.2	55.4 ± 5.1	
CO_2-FFI	17.3 ± 1.4	20.3 ± 1.6	23.6 ± 1.9	28.9 ± 2.3	35.4 ± 2.8	36.3 ± 2.9	37.8 ± 3.0	38.2 ± 3.0
CO_2-LULUCF	5.2 ± 3.7	5.1 ± 3.6	5.7 ± 4.0	5.2 ± 3.6	4.9 ± 3.4	4.1 ± 2.9	3.6 ± 2.5	4.2 ± 2.8
CH_4	6.3 ± 1.9	6.7 ± 2	7.2 ± 2.2	7.7 ± 2.3	8.4 ± 2.5	8.7 ± 2.6	9.2 ± 2.7	
N_2O	1.9 ± 1.1	2.2 ± 1.3	2.3 ± 1.4	2.5 ± 1.5	2.7 ± 1.6	2.8 ± 1.7	2.9 ± 1.7	
UNFCCC F-gases	0.2 ± 0.01	0.4 ± 0.1	0.5 ± 0.2	0.8 ± 0.3	1.4 ± 0.4	1.6 ± 0.5	1.9 ± 0.6	

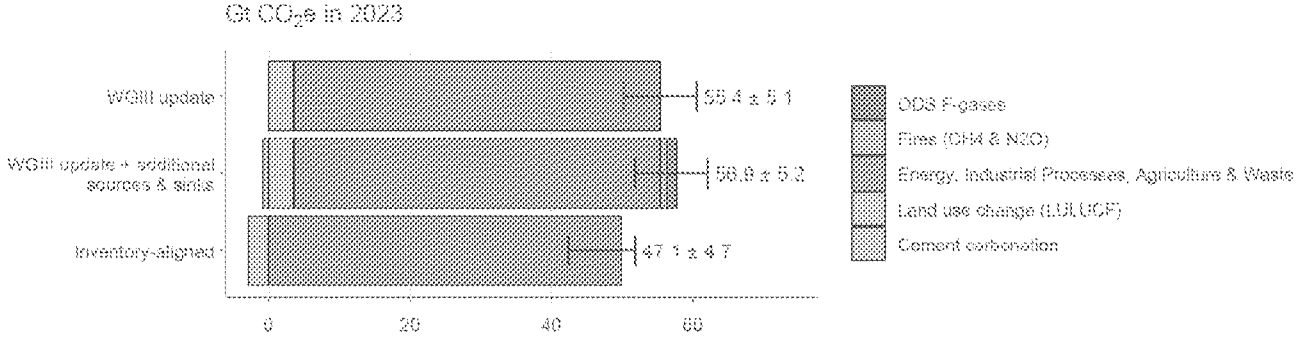

Figure 3. Annual global anthropogenic greenhouse gas emissions by assessment convention in 2023. Refer to Table 1 for a list of underlying datasets. Differences between conventions are primarily due to differences in system boundaries (Lamb et al., 2025). Uncertainties are ±8 % for CO_2-FFI, ±70 % for CO_2-LULUCF, ±30 % for CH_4 and F-gases, and ±60 % for N_2O, corresponding to a 90 % confidence interval.

primary SLCFs (NO_x, CO, non-methane VOCs (NMVOCs), SO_2, BC and OC) since the COVID hiatus in emissions, except for NH_3, whose emissions are steadily increasing. SLCF emissions from biomass burning are taken from GFED (van der Werf et al., 2017) with small fires (GFED4.1s) updated to 2024 (following AR6 WGIII; Dhakal et al., 2022). Estimates from GFED for 2017 to 2024 are provisional and will be updated with GFED5 in future datasets, which will provide substantially higher emissions for most species. The estimate of global carbon emissions due to wildfires in 2024 is slightly lower than in 2023 (both were higher than average fire years). These lower overall carbon emissions in 2024 hide an increase in CO_2 emissions (accompanied by an increase in NO_x emissions) but a decrease in CH_4 and CO emissions accompanied by a decrease in carbonaceous aerosols and NMVOC emissions.

The decrease in global NO_x emissions, despite very heterogeneous regional trends (Szopa et al., 2021), is confirmed by global NO_2 satellite observations from OMI (tropospheric NO_2 column from OMI visualised through the Giovanni system, Acker and Leptoukh, 2007). The trends in global CO concentration are less clear. Surface data from MOPITT and AIRS show a slight increase over the last 3 years. CO does not result solely from CO emissions but also from VOCs including methane oxidation, which can explain differences in trends between emissions and concentrations.

Overall, the trends in emissions were similar (see Supplement Sect. S4) over the 2020–2023 period in the most recent CEDS dataset to our previous estimate (Forster et al., 2024) but with a lower post COVID rebound for NO_x and SO_2. Regarding SO_2, the CEDS datasets (v2024_04_01 used in Forster et al., 2024 and v2025_03_18 used here) account for the introduction of strict fuel sulfur controls brought in by the International Maritime Organization in January 2020. Total SO_2 emissions in 2019 were 80.9 Tg SO_2 (Table 2). The SO_2 emissions from international shipping declined by 8.4 Tg SO_2 from 10.4 Tg SO_2 in 2019 to 2.0 Tg SO_2 in 2020, which is close to the expected 8.5 Tg SO_2 reduction estimated by the International Maritime Organization. This decrease was estimated at 7.4 Tg SO_2 in the previous CEDS version used in Forster et al. (2024). More generally, the reduction pace of the global SO_2 emission over the last 10 years corresponds to that of the first 10 years of the SSP scenarios assuming strong air pollution control (SSP1 and SSP5).

Using our combined estimate of GFED and CEDS (with a 2024 extrapolation based on CAMS), emissions of all SLCFs were reduced in 2022 relative to 2019 but rebounded in 2023

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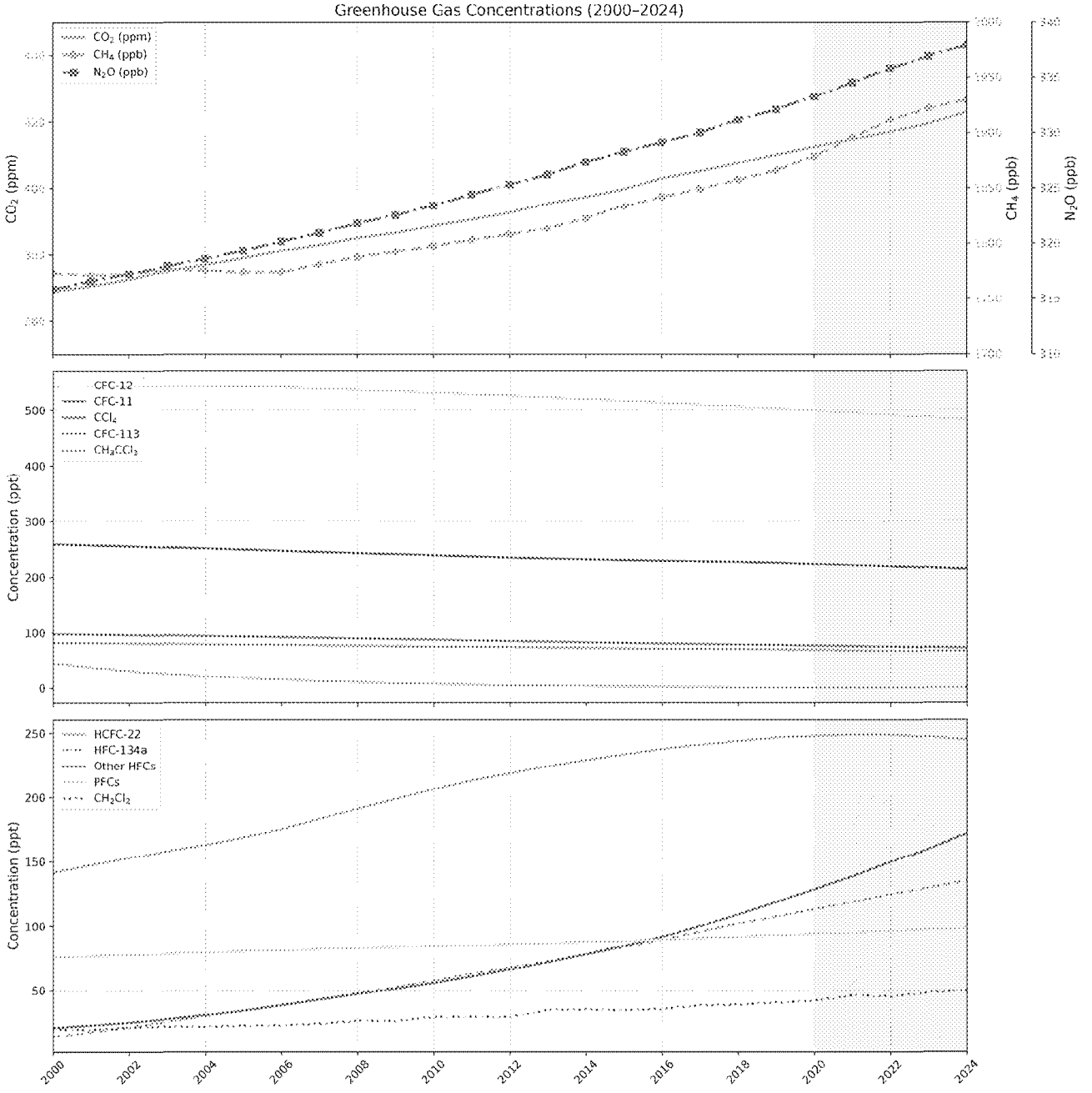

Figure 4. Atmospheric concentrations of a set of well-mixed greenhouse gases over 2000–2024. The grey shaded region represents continuing changes since AR6. Note the different vertical scales.

and then slightly decreased in 2024 (relative to 2023) for all compounds except NO_x, whose increase is partly driven by increased emissions from biomass burning (Table 2 and Sect. S4). 2023 was a record year for emissions of organic carbon (driven again by a very active biomass burning season) and ammonia (driven by a steady background increase in agricultural sources and a contribution from biomass burning). Fires can be worsened by climate change because of increased fire-prone weather conditions (Burton et al., 2024). Strictly speaking, such fires could sometimes be considered feedbacks and not be included in anthropogenic forcings. However, we choose to include fires in our tracking, as historical biomass burning emissions inventories have previously been consistently treated as an anthropogenic forcing (for example in CMIP6), though this assumption may need to be revisited in the future (see also discussion in Sect. 5). This differs from the treatment of accounting for CO_2 and CH_4 emissions at present (Sect. 2.2), where we do not include nat-

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ural emissions in the inventories. As described in Sect. 5, this treatment of all biomass burning emissions as a forcing has implications for several categories of anthropogenic radiative forcing.

Uncertainties associated with these emission estimates are difficult to quantify. From the non-biomass-burning sectors they are estimated to be smallest for SO_2 (±14 %), largest for black carbon (BC) (a factor of 2) and intermediate for other species (Smith et al., 2011; Bond et al., 2013; Hoesly et al., 2018). Relative uncertainties are also likely to increase both backwards in time (Hoesly et al., 2018) and again in the most recent years. Future updates of CEDS are expected to include uncertainties (Hoesly et al., 2018).

5 Effective radiative forcing (ERF)

ERFs were principally assessed in Chap. 7 of AR6 WGI (Forster et al., 2021), which focussed on assessing ERF from changes in atmospheric concentrations; it also supported estimates of ERF in Chap. 6 that attributed forcing to specific precursor emissions (Szopa et al., 2021) and generated the time history of ERF shown in AR6 WGI Fig. 2.10 and discussed in Chap. 2 (Gulev et al., 2021).

The ERF calculation follows the methodology used in AR6 WGI (Smith et al., 2021b) as updated by Forster et al. (2024) and described in Sect. S5). One methodological update is incorporated into IGCC 2024 for the ERF from land-use surface reflection and irrigation (Sect. S5.4). For each category of forcing, a 100 000-member probabilistic Monte Carlo ensemble is sampled to span the assessed uncertainty range in each forcing. Uncertainties account for systematic, structured random and random components. All uncertainties are reported as 5 %–95 % ranges and provided in square brackets. The methods are all detailed in Sect. S5.

The summary results for the anthropogenic constituents of ERF and solar irradiance in 2024 relative to 1750 are shown in Fig. 5a. In Table 3 these are summarised alongside the equivalent ERFs from AR6 (1750–2019) and last year's Climate Indicators update (1750–2023). Figure 5b shows the time evolution of ERF from 1750 to 2024.

Total anthropogenic ERF has increased to 2.97 [2.05 to 3.77] $W m^{-2}$ in 2024 relative to 1750, compared to 2.72 [1.96 to 3.48] $W m^{-2}$ for 2019 relative to 1750 in AR6. The ERF has increased considerably from the 2023 estimate of 2.79 [1.79 to 3.61] $W m^{-2}$. 2023 was a year associated with high biomass burning aerosol, which resulted in a stronger negative aerosol forcing than recent trends. Biomass burning was also high in 2024 but lower than 2023 levels. Sulfur emissions from shipping have declined since 2020, weakening the aerosol ERF and adding around +0.1 $W m^{-2}$ over 2020 to 2024 (see Sects. 7.2, S5 and S7). The approach of including all biomass burning aerosols is consistent with reporting ERF based on concentration increase in GHGs independent of whether CO_2 and CH_4 are caused by anthropogenic emissions or a smaller part is caused by any feedbacks such as from biomass burning fires or wetlands. Changes in mineral dust and sea salt are not easily relatable to human activity and are not included in the ERF of aerosols.

The ERF from well-mixed GHGs is 3.54 [3.22 to 3.85] $W m^{-2}$ for 1750–2024, of which 2.33 $W m^{-2}$ is from CO_2, 0.57 $W m^{-2}$ from CH_4, 0.23 $W m^{-2}$ from N_2O and 0.41 $W m^{-2}$ from halogenated gases. This is an increase of around 7 % from 3.32 [3.03 to 3.61] $W m^{-2}$ for 1750–2019 in AR6. ERFs from CO_2, CH_4 and N_2O have all increased since the AR6 WG1 assessment for 1750–2019, owing to increases in atmospheric concentrations.

The total aerosol ERF (sum of the ERF from aerosol–radiation interactions (ERFari's) and aerosol–cloud interactions (ERFaci's)) for 1750–2024 is −1.07 [−1.90 to −0.43] $W m^{-2}$ compared to −1.18 [−2.10 to −0.49] $W m^{-2}$ for 1750–2023 (Forster et al., 2024) and −1.06 [−1.71 to −0.41] $W m^{-2}$ assessed for 1750–2019 in AR6 WGI. Attributing year-to-year trends to aerosol forcing is problematic due to the variability in biomass burning emissions. Increasing biomass burning emissions since AR6 have been mostly offset by a decrease in emissions from energy and industrial sectors, leading to best estimates of ERFari and ERFaci that are virtually unchanged from the 1750–2019 AR6 assessment to the 1750–2024 determination here (Table 3).

Ozone ERF is determined to be 0.50 [0.25 to 0.75] $W m^{-2}$ for 1750–2024, slightly higher than the AR6 assessment of 0.47 [0.24 to 0.71] $W m^{-2}$ for 1750–2019. This is due to the increase in emissions of some of its precursors (CO, VOCs, CH_4), but this result is highly uncertain since consolidated ozone trends are not yet released. Stratospheric water vapour from methane oxidation has not changed (to two decimal places) since AR6. ERF from light-absorbing particles on snow and ice is 0.08 [0.00 to 0.19] $W m^{-2}$ for 1750–2024, like AR6. We determine from provisional data that aviation activity in 2024 returned to pre-COVID levels (IATA, 2024). Therefore, ERF from contrails and contrail-induced cirrus is the same as in AR6, at 0.06 [0.02 to 0.10] $W m^{-2}$ in 2024. The methodology to determine land-use ERF has been updated (Sect. S5.4), but this forcing has a similar best estimate to 2023 and AR6, with a wider uncertainty range that accounts for the separate assessment of irrigation forcing.

The headline assessment of solar ERF has not been re-assessed, at 0.01 [−0.06 to +0.08] $W m^{-2}$ from pre-industrial times to the 2009–2019 solar cycle mean (Table 3). Separate to the assessment of solar forcing over complete solar cycles, we provide a single-year solar ERF for 2024 of +0.09 [+0.01 to +0.17] $W m^{-2}$ (Fig. 5a). This is higher than the single-year estimate of solar ERF for 2019 (a solar minimum) of −0.02 [−0.08 to 0.06] $W m^{-2}$.

Volcanic ERF is included in the overall time series (Fig. 5b), but following IPCC convention we do not provide a single-year estimate for 2024 given the sporadic nature of volcanoes. Alongside the time series of stratospheric aerosol optical depth derived from proxies and satellite products, for

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Table 2. Emissions of the major SLCFs in 1750, 2019 and 2024 from a combination of CEDS and GFED. Emissions of SO_2+ SO_4 use SO_2 molecular weights. Emissions of NO_x use NO_2 molecular weights. VOCs are for the total mass. Note that estimates for previous years have been revised and updated. WGI 2019 estimates from Smith et al. (2021a).

Compound	SLCF emissions ($Tg\,yr^{-1}$)				
	1750	2019 (WGI for ERF estimates)	2019 (updated)	2023 (updated)	2024 (updated)
Sulfur dioxide (SO_2)+ sulfate (SO_4^{2-})	2.8	83.7	80.9	72.7	71.2
Black carbon (BC)	2.1	7.8	7.3	7.6	7.5
Organic carbon (OC)	15.5	29.8	33.0	41.0	36.1
Ammonia (NH_3)	6.6	64.9	66.3	72.7	70.6
Oxides of nitrogen (NO_x)	19.4	135.3	133.6	128.4	130.4
Volatile organic compounds (VOCs)	60.9	209.1	204.8	224.1	212.7
Carbon monoxide (CO)	348.4	855.0	816.1	896.0	845.3

Table 3. Contributions to anthropogenic effective radiative forcing (ERF) for 1750–2024 assessed in this section. Data are for single-year estimates unless specified. All values are in watts per square metre ($W\,m^{-2}$), and 5 %–95 % ranges are in square brackets. As a comparison, the equivalent assessments from AR6 (1750–2019) and last year's climate indicators (1750–2023) are shown. Solar ERF is included and unchanged from AR6, based on the most recent solar cycle (2009–2019), thus differing from the single-year estimate in Fig. 5a. Volcanic ERF is excluded due to the sporadic nature of eruptions.

Forcer	1750–2019 [$W\,m^{-2}$] (AR6)	1750–2023 (Forster et al., 2024)	1750–2024 [$W\,m^{-2}$]	Reason for change since last year [$W\,m^{-2}$]
CO_2	2.16 [1.90 to 2.41]	2.28 [2.01 to 2.56]	2.33 [2.05 to 2.61]	Increases in GHG concentrations resulting from increases in emissions
CH_4	0.54 [0.43 to 0.65]	0.56 [0.45 to 0.68]	0.57 [0.45 to 0.68]	
N_2O	0.21 [0.18 to 0.24]	0.22 [0.19 to 0.26]	0.23 [0.20 to 0.26]	
Halogenated GHGs	0.41 [0.33 to 0.49]	0.41 [0.33 to 0.49]	0.41 [0.33 to 0.49]	
Ozone	0.47 [0.24 to 0.71]	0.51 [0.25 to 0.76]	0.50 [0.25 to 0.75]	
Stratospheric water vapour	0.05 [0.00 to 0.10]	0.05 [0.00 to 0.10]	0.05 [0.00 to 0.11]	
Aerosol–radiation interactions	−0.22 [−0.47 to +0.04]	−0.26 [−0.50 to −0.03]	−0.22 [−0.44 to +0.01]	Decrease in most aerosol and aerosol precursor emissions (Table 2)
Aerosol–cloud interactions	−0.84 [−1.45 to −0.25]	−0.91 [−1.80 to −0.27]	−0.85 [−1.65 to −0.25]	
Land use (surface albedo changes and effects of irrigation)	−0.20 [−0.30 to −0.10]	−0.20 [−0.31 to −0.10]	−0.19 [−0.30 to −0.05]	Separation of albedo and irrigation components; updated data source and methodology
Light-absorbing particles on snow and ice	0.08 [0.00 to 0.18]	0.08 [0.00 to 0.17]	0.08 [0.00 to 0.19]	
Contrails and contrail-induced cirrus	0.06 [0.02 to 0.10]	0.05 [0.02 to 0.09]	0.06 [0.02 to 0.10]	
Total anthropogenic	2.72 [1.96 to 3.48]	2.79 [1.78 to 3.61]	2.97 [2.05 to 3.77]	Increasing positive GHG forcing and decreasing negative aerosol forcing
Solar irradiance	0.01 [−0.06 to 0.08]	0.01 [−0.06 to 0.08]	0.01 [−0.06 to 0.08]	

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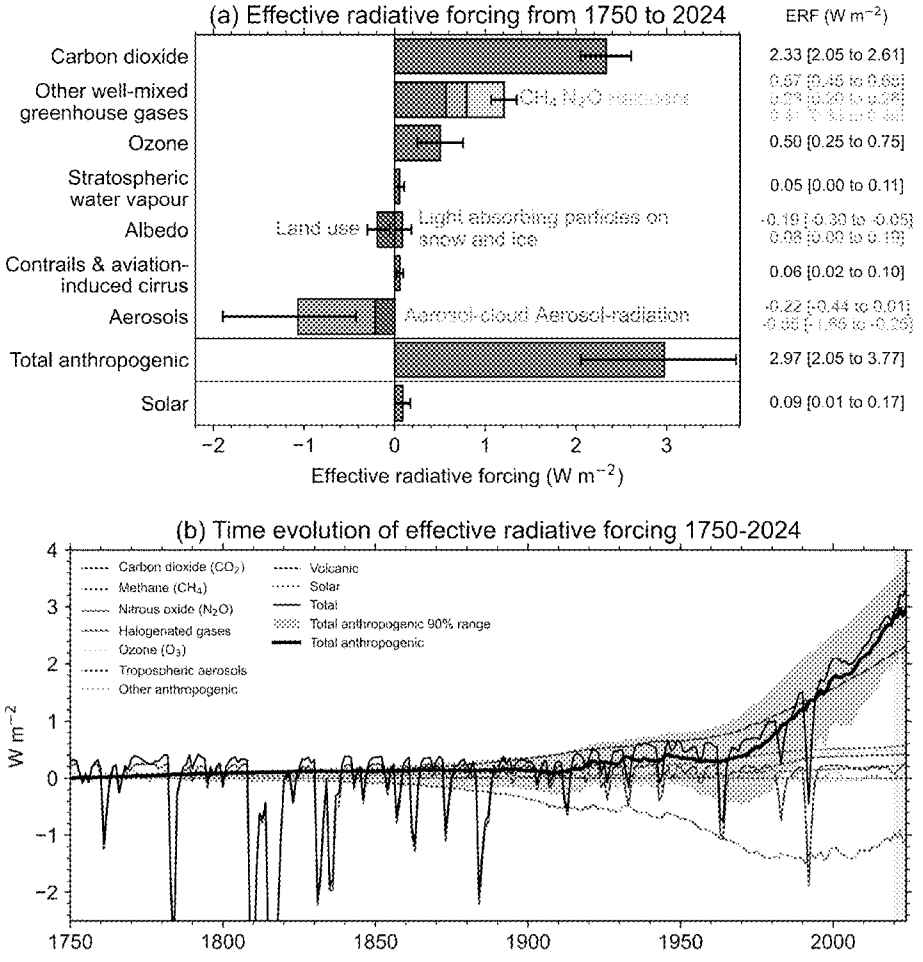

Figure 5. Effective radiative forcing (ERF) from 1750–2024. **(a)** 1750–2024 change in ERF, showing best estimates (bars) and 5 %–95 % uncertainty ranges (lines) from major anthropogenic components to ERF, total anthropogenic ERF and solar forcing. Note that solar forcing in 2024 is a single-year estimate and hence differs from Table 3. **(b)** Time evolution of ERF from 1750 to 2024. Best estimates from major anthropogenic categories are shown along with solar and volcanic forcing (thin coloured lines), total (thin black line), and anthropogenic total (thick black line). The 5 %–95 % uncertainty in the anthropogenic forcing is shown by grey shading.

2022–2024 we include the stratospheric water vapour contribution from the Hunga Tonga–Hunga Ha'apai (HTHH) eruption derived from Microwave Limb Sounder (MLS) data. We estimate a net positive (positive forcing from stratospheric water vapour more than outweighing negative forcing from stratospheric aerosols) forcing from HTHH through 2024 (Sect. S5), though note that other studies find the net HTHH forcing to be negative (Gupta et al., 2025) or close to zero (Schoeberl et al., 2024).

6 Earth energy imbalance (EEI)

EEI, assessed in Chap. 7 of AR6 WGI (Forster et al., 2021), provides a measure of accumulated surplus energy (heating) in the climate system and is hence an essential indicator to monitor the current and future status of global warming. It represents the difference between the radiative forcing acting to warm the climate, and Earth's radiative response, which acts to oppose this warming. Under stable climate conditions, i.e. in the absence of anthropogenic climate forcing, this difference would be balanced over interdecadal timescales. Since at least 1970 there has been a persistent imbalance in the energy flows that has led to excess energy being absorbed by the climate system (Forster et al., 2021). On annual and longer timescales, the global Earth heat inventory changes associated with EEI are dominated by the changes in global ocean heat content (OHC), which has accounted for about 90 % of global heating since the 1970s (Forster et al., 2021). This planetary heating results in changes in all components of the Earth system such as sea-level rise, ocean warming, ice loss, rises in temperature and water vapour in the atmosphere, changes in ocean and atmospheric circulation, continental warming and permafrost thawing (e.g. Cheng et al., 2022; von Schuckmann et al., 2023), with adverse impacts

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for ecosystems and human systems (Douville et al., 2021; IPCC, 2022).

On decadal timescales, changes in global surface temperatures (Sect. 5) can become decoupled from EEI by ocean heat rearrangement processes (e.g. Palmer and McNeall, 2014; Allison et al., 2020). Therefore, the increase in the Earth heat inventory arguably provides a more robust indicator of the rate of global change on interannual-to-decadal timescales (Cheng et al., 2019; Forster et al., 2021; von Schuckmann et al., 2023). AR6 WGI found increased confidence in the assessment of change in the Earth heat inventory compared to previous IPCC reports due to observational advances and joint closure of the energy and global sea-level budgets (Forster et al., 2021; Fox-Kemper et al., 2021).

AR6 estimated that EEI increased from 0.50 [0.32–0.69] $W m^{-2}$ during the period 1971–2006 to 0.79 [0.52–1.06] $W m^{-2}$ during the period 2006–2018 (Forster et al., 2021). The contributions to increases in the Earth heat inventory throughout 1971–2018 remained stable: 91 % for the full-depth ocean, 5 % for the land, 3 % for the cryosphere and about 1 % for the atmosphere (Forster et al., 2021). Two recent studies demonstrated independently and consistently that since 1960, the rate of warming of the world ocean has been increasing at a relatively consistent pace of $0.15 \pm 0.05 W m^{-2}$ per decade (Minière et al., 2023; Storto and Yang, 2024; Merchant et al., 2025), while the rate of warming for the land, cryosphere and atmosphere has been increasing at rate of $0.013 \pm 0.003 W m^{-2}$ per decade (Minière et al., 2023). The increase in EEI over the last several decades (Fig. 6) has also been reported by Cheng et al. (2019), von Schuckmann et al. (2020, 2023), Loeb et al. (2021), Hakuba et al. (2021), Kramer et al. (2021), Raghuraman et al. (2021) and Minère et al. (2023). The observed increase in EEI over the most recent period (i.e. past 2 decades) is helping to drive exceptionally warm conditions (Sect. 7; Minobe et al., 2025). The increase in EEI has been linked to rising concentrations of well-mixed GHGs and recent reductions in aerosol emissions (Sect. 5; Raghuraman et al., 2021; Kramer et al., 2021; Hansen et al., 2023) and to an increase in absorbed solar radiation associated with decreased reflection by clouds and sea ice and a decrease in outgoing longwave radiation (OLR) due to increases in trace gases and water vapour (Loeb et al., 2021; Goessling et al., 2025; Allan and Merchant, 2025).

We carry out an update to the AR6 estimate of changes in the Earth heat inventory based on updated observational time series for the period 1971–2020 (Table 4 and Fig. 6). Time series of heating associated with loss of ice and warming of the atmosphere and continental land surface are obtained from the recent Global Climate Observing System (GCOS) initiative (von Schuckmann et al., 2023; Cuesta-Valero et al., 2023; Vanderkelen and Thiery, 2022; Nitzbon et al., 2022; Kirchengast et al., 2022). We use the original AR6 time series ensemble OHC time series for the period 1971–2018 and then an updated five-member ensemble for the period 2019–2024. We "splice" the two sets of time series by adding an offset as needed to ensure that the 2018 values are identical. The AR6 heating rates and uncertainties for the ocean below 2000 m are assumed to be constant throughout the period. The time evolution of the Earth heat inventory is determined as a simple summation of time series of atmospheric heating; continental land heating; heating of the cryosphere; and heating of the ocean over three depth layers – 0–700, 700–2000 and greater than 2000 m (Fig. 6a). While von Schuckmann et al. (2023) have also quantified heating of permafrost and inland lakes and reservoirs, these additional terms are small and not included here for consistency with AR6 (Forster et al., 2021).

Table 4. Estimates of the Earth energy imbalance (EEI) for AR6 and the present study.

Time period	Earth energy imbalance ($W m^{-2}$). Square brackets show 90 % confidence intervals.	
	IPCC AR6	This study
1971–2018	0.57 [0.43 to 0.72]	0.57 [0.43 to 0.72]
1971–2006	0.50 [0.32 to 0.69]	0.50 [0.31 to 0.68]
2006–2018	0.79 [0.52 to 1.06]	0.79 [0.52 to 1.07]
1977–2024	–	0.68 [0.52 to 0.85]
2012–2024	–	0.99 [0.70 to 1.28]

In our updated analysis, we find successive increases in EEI for each 20-year period since 1975, with an estimated value of 0.43 [0.03 to 0.83] $W m^{-2}$ during 1975–1994 that more than doubled to 0.89 [0.7 to 1.09] $W m^{-2}$ during 2005–2024 (Fig. 6b). In addition, there is some evidence that the warming signal is propagating into the deeper ocean over time, as seen by a robust increase in ocean warming in the 700–2000 m depth layer since the 1990s (von Schuckmann et al., 2020, 2023; Cheng et al., 2019, 2022). The model simulations qualitatively agree with the observational evidence (e.g. Gleckler et al., 2016; Cheng et al., 2019), further suggesting that more than half of the OHC increase since the late 1800s occurs after the 1990s.

The update of the AR6 assessment periods to end in 2024 results in systematic increases of EEI: 0.68 $W m^{-2}$ during 1977–2024 compared to 0.57 $W m^{-2}$ during 1971–2018 and 0.99 $W m^{-2}$ during 2012–2024 compared to 0.79 $W m^{-2}$ 2006–2018 (Table 4). The trend and interannual variability of EEI can largely be explained by a combination of surface temperature changes and radiative forcing (Hodnebrog et al., 2024). However, there was a jump in 2023 and 2024, which is still being investigated (see Sect. 7.2) but which is also discussed in the light of recent exceptional extreme climate conditions (Minobe et al., 2025).

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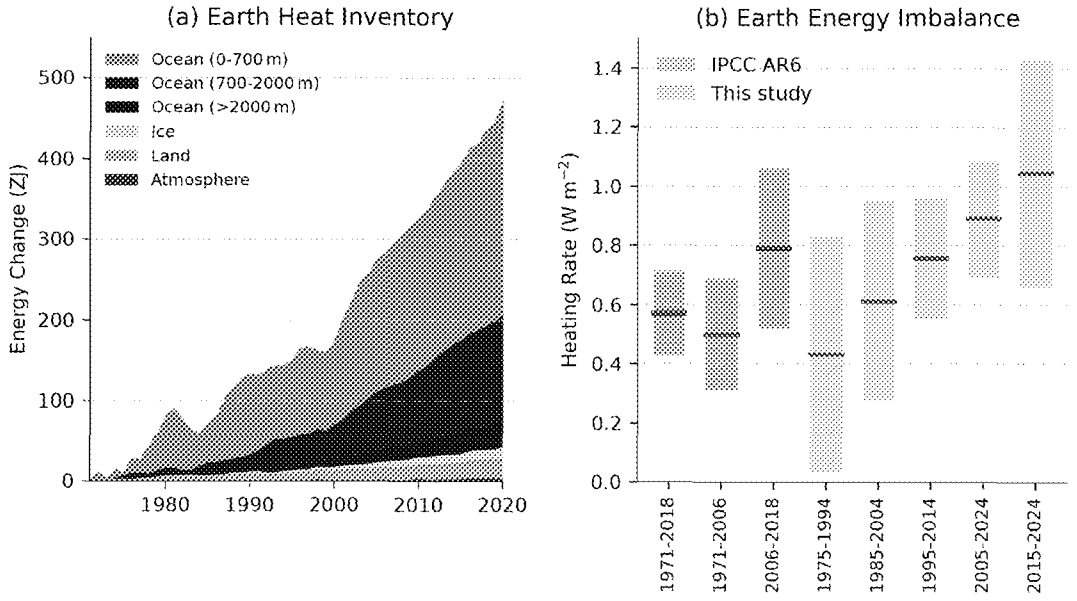

Figure 6. **(a)** Observed changes in the Earth heat inventory for the period 1971–2020, with component contributions as indicated in the figure legend. **(b)** Estimates of the Earth energy imbalance for the IPCC AR6 assessment periods, for consecutive 20-year periods and the most recent decade. Shaded regions indicate the *very likely* range (90 % to 100 % probability). Data use and approach are based on the AR6 methods and further described in Sect. S6. For the IPCC AR6 periods our assessment closely matches that in AR6. Note the periods in our assessment overlap with different IPCC AR6 periods.

7 Observed surface temperature change

7.1 Change since 1850–1900

AR6 WGI Chap. 2 assessed the 2001–2020 globally averaged surface temperature change above an 1850–1900 baseline to be 0.99 [0.84 to 1.10] °C and 1.09 [0.95 to 1.20] °C for 2011–2020 (Gulev et al., 2021). Updated estimates to 2013–2022 of 1.15 [1.00–1.25] °C were given in AR6 SYR (IPCC, 2023c), matching the estimate in Forster et al. (2023).

There are choices around the methods used to aggregate surface temperatures into a global average, how to correct for systematic errors in measurements, methods of infilling missing data, and whether surface measurements or atmospheric temperatures just above the surface are used. These choices, and others, affect temperature change estimates and contribute to their uncertainty (AR6 WGI Chap. 2, Cross Chap. Box 2.3, Gulev et al., 2021). The methods chosen here closely follow AR6 WGI and are presented in the Supplement, Sect. S7. Confidence intervals are taken from AR6 as only one of the employed datasets regularly updates ensembles (see Supplement, Sect. S7).

Based on the updates available as of March 2025, the change in global surface temperature from 1850–1900 to 2015–2024 is presented in Fig. 7. These data, using the same underlying datasets (with some version changes: see Sect. S7) and methodology as AR6, estimate 1.24 [1.11–1.35] °C of warming, an increase of 0.15 °C within 4 years from the 2011–2020 value reported in AR6 WGI (Table 5) or 0.14 °C from the 2011–2020 value in the most recent dataset version. The decade 2015–2024 was 0.31 °C warmer than the previous decade (2005–2014). These changes, although amplified somewhat by the exceptionally warm years in 2023 and 2024, are broadly consistent with typical warming rates over the last few decades, which were assessed in AR6 as 0.76 °C over the 1980–2020 period (using ordinary-least-square linear trends) or 0.019 °C per year (Gulev et al., 2021). They are also broadly consistent with projected warming rates from 2001–2020 to 2021–2040 reported in AR6, which have a very likely range between 0.016 °C per year and 0.036 °C per year under SSP2-4.5 (Lee et al., 2021, their Table 4.5), and with human-induced warming rates discussed in Sect. 8.4.

Land temperatures increased by 1.79 [1.56–2.03] °C from 1850–1900 to 2015–2024 and ocean temperatures by 1.02 [0.81–1.13] °C over the same period, implying that most land areas have already experienced more than 1.5 °C of warming from the 1850–1900 period. As was the case for the periods reported in AR6, the ratio of observed land to ocean warming is in the vicinity of 1.75, somewhat higher than the ratio of 1.5 [1.4–1.7] projected by the end of the century in CMIP6 models (AR6, their Table 4.2 and Sect. 4.5.1.1.1). The additional observed warming since 2020 in the most recent dataset versions (0.21 °C for land, 0.13 °C for ocean) has a ratio within the CMIP6 projection range.

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Table 5. Estimates of global surface temperature change from 1850–1900 [very likely (90 %–100 % probability) ranges] for IPCC AR6 and the present study.

Time period	Temperature change from 1850–1900 (°C)	
	IPCC AR6 (as reported)	This study
Global, most recent 10 years	1.09 [0.95 to 1.20] (to 2011–2020)	1.24 [1.11 to 1.35] (to 2015–2024)
Global, most recent 20 years	0.99 [0.84 to 1.10] (to 2001–2020)	1.09 [0.93 to 1.20] (to 2005–2024)
Land, most recent 10 years	1.59 [1.34 to 1.83] (to 2011–2020)	1.79 [1.56 to 2.03] (to 2015–2024)
Ocean, most recent 10 years	0.88 [0.68 to 1.01] (to 2011–2020)	1.02 [0.81 to 1.13] (to 2015–2024)

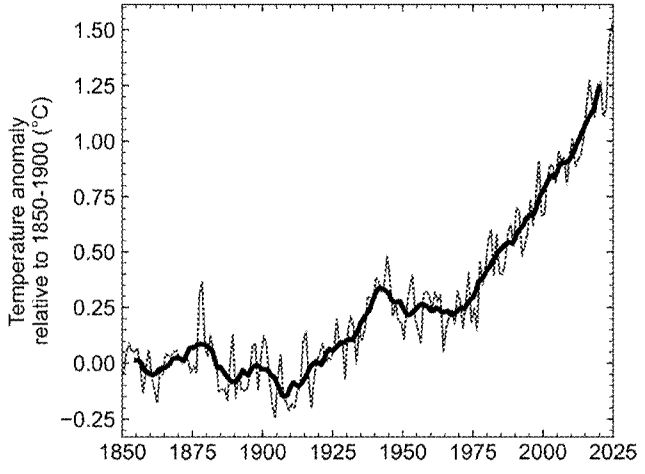

Figure 7. Annual (thin line) and decadal (thick line) means of global surface temperature (expressed as a change from the 1850–1900 reference period). Temperatures are based on an average of four datasets following AR6; see Sect. S7 for details.

7.2 2023–2024 global mean temperature anomalies

At the time, 2023 set a new global annual-mean surface temperature change record, with a best estimate of 1.44 °C, beating 2016 by 0.16 °C. 2024 surpassed this, reaching 1.52 ± 0.13 °C, becoming the first calendar year since pre-industrial times more likely than not exceeding 1.5 °C (Fig. 7). The assessed uncertainty range is based on that in AR6 WGI (Gulev et al., 2021). All four individual datasets are well inside the range (ranging from 1.46 to 1.56 °C). Natural drivers and internal variability are expected to modulate human-caused warming at interannual-to-decadal timescales. 2024 is assessed to be 0.16 °C warmer than the updated human-induced value (Table 6), while 2022 was 0.06 °C colder. These values are not inconsistent with AR6, which estimated the effect of internal variability in any single year to be ±0.25 °C based on CMIP6 models, nor with the lower estimated ranges (±0.17 °C) when calculated from observational products (Trewin, 2022).

The probability of seeing an observed temperature of 1.52 °C in 2024 considering a human-induced warming equal to 1.36 °C is about one chance out of six (Fig. 8a). The methodology to calculate this probability consists in comparing the global surface air temperature (GSAT)-observed anomaly to the anomalies expected from CMIP6 models following the framework adopted in AR6 in Chap. 3 (Eyring et al., 2021) for decadal trends and adapted here for interannual timescale issues. The same probability but conditional to the fact that 2024 followed an El Niño year and that the Atlantic multidecadal variability (AMV) was in a positive phase (Sect. S7), rises to one chance out of two. 2024 can therefore be treated as a "normal" year, i.e. very much expected at the actual human-caused global warming level when the internal modes of variability are taken into account and when assessed from a very large number of simulations from large ensembles. Based on the same calculation, we estimate that a year as warm as 2023 would occur once in 4 years at human-induced warming equal to 1.31 °C (Fig. 8b). It drops to a 1-in-14 [10–20, CI 5 %–95 %]-year event, i.e. a rare-to-exceptional event, when considering that 2023 followed a La Niña year and despite persistent positive AMV. Note that the probability of the large jump in global temperatures was increased by the fact that the El Niño followed an extended La Niña over 2020–2022 (Raghuraman et al., 2024). Within such a framework, 2022, which was colder than human-induced warming, could be interpreted as a normal/expected year considering that 2021 was a La Niña year and AMV positive (Fig. 8c). These results show that human-induced warming combined with particular modes of natural variability shifts the odds of global surface temperatures passing 1.5 °C, making it more likely. Section 8 has a fuller discussion of human-induced warming.

The increase in global temperature between 2022 and 2023 and in particular in global sea surface temperature is exceptional based on model estimates accounting for projected

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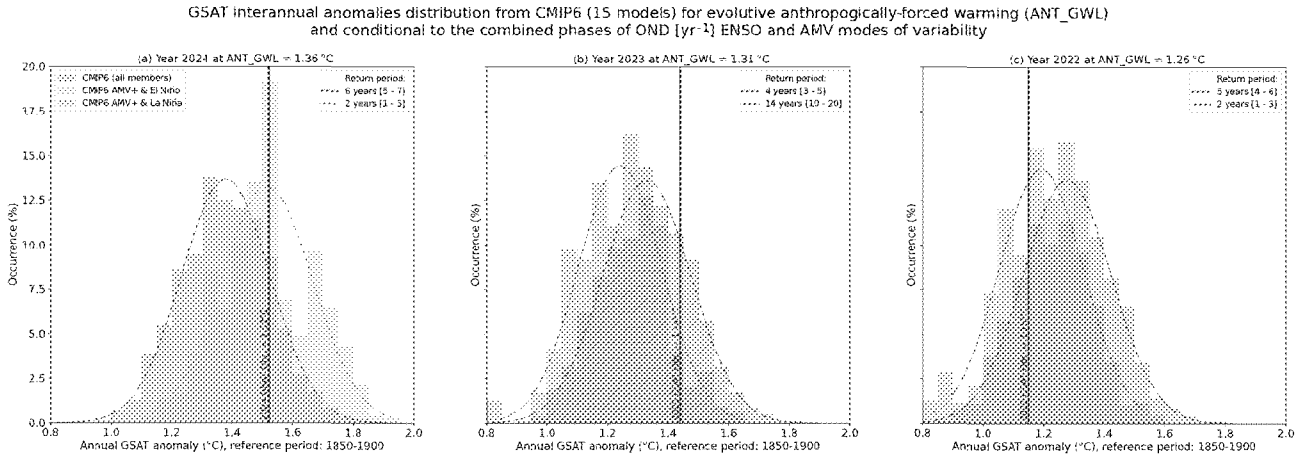

Figure 8. **(a)** Grey histograms of global surface air temperature (GSAT) interannual anomalies estimated from 15 CMIP6 models extracted from all available SSP scenarios ($\sim$ 700 members) at anthropogenic global warming levels (ANT_GWL) corresponding to **(a)** 2024, **(b)** 2023 and **(c)** 2022. The red vertical bar stands for the observational consolidated GSAT annual anomalies (Sect. 7.1). The return period of the observed annual GSAT event estimated from the CMIP6 distribution is provided (upper corner). Associated [5 %–95 %] likely range is assessed through bootstrapping. Interannual anomalies are obtained following the Trewin (2022) method over 10-year sliding windows. Only models providing large ensembles (n members > 5) and having at least one member whose interannual variance of GSAT is compatible with observational estimates are selected. Coloured histograms stand for the same distribution but conditional to the combined phase of El Niño–Southern Oscillation (ENSO) and Atlantic Multidecadal Variability (AMV). Sea surface temperature (SST) anomalies for the modes of variability are calculated from the residual of SST obtained after removing the modelled forced response estimated as model ensemble mean. A year is considered an El Niño/La Niña year if the (October–December) Oceanic Niño Index (ONI) index of the previous year is greater/lower than 1 standard deviation. A year is considered an AMV+ year if the annual North Atlantic average SST is greater than 1 standard deviation. Light pink represents years when ONI and AMV are concomitantly positive and light blue when ONI is negative.

known human and natural forcings and internal variability (Rantanen and Laaksonen, 2024; Terhaar et al., 2025, Cattiaux et al., 2024). The La Niña-to-El Niño sequence is of key importance and has been likely reinforced by enhanced energy uptake due to multi-year persistence in the preceding La Niña. The temporal synchronicity between the modes of variability in all basins is hypothesised to have played a role in the jump (Minobe et al., 2025), with the North Atlantic being at a record warm (Guinaldo et al., 2025) and the austral sea ice extent being at a record low (Purich and Doddridge, 2023).

Possible specific causes beyond internal variability, many of which are already accounted for in the estimated human-induced warming level, have been postulated, e.g. International Maritime Organization rules on shipping fuel sulfur content that came into force in January 2021, the eruption of Hunga Tonga–Hunga Ha'apai in January 2022 and other subsequent smaller volcanic activity, and a faster-than-expected onset of solar cycle 25 (see Sect. S7 for details and references). A key diagnostic of these changes including both external forcing and internal variability was the exceptional magnitude of the net energy increase into the Earth system from mid-2022 to mid-2023, driven in large part by the reduced reflectance and greater absorption of solar radiation (Hodnebrog et al., 2024; Goessling et al., 2025; Minobe et al., 2025; Allan and Merchant, 2025), which may be influenced by cloud feedbacks (Tselioudis et al., 2024) as well as surface reflectance and atmospheric composition change (see also Sect. 6).

Our analysis, detailed in the Supplement, Sect. S7, makes use of estimates of variability and radiative forcing contributions and their uncertainty based on Sect. 5 and the published literature. It shows that the increase in 2023 and 2024 compared to previous years could be explained by a combination of factors. In summary, our analyses show that, although the relative weight between the physical processes in explaining the high surface temperatures remain to be better quantified, the 2023 and 2024 observed temperatures are not inconsistent with the level of human-induced warming assessed next, in Sect. 8.

8 Human contribution to surface temperature change

Human-induced warming, also known as anthropogenic warming, refers to the component of observed global surface temperature increase attributable to both the direct and indirect effects of human activities, which are typically grouped as follows: well-mixed GHGs (consisting of CO_2, CH_4, N_2O and F-gases) and other human forcings (consisting of aerosol–radiation interaction, aerosol–cloud interaction, black carbon on snow, contrails, ozone, stratospheric H_2O and land use) (Eyring et al., 2021). The remaining contributors to total warming are natural: consisting of both natu-

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ral forcings (such as solar and volcanic activity) and internal variability of the climate system (such as variability related to El Niño/La Niña events).

An assessment of human-induced warming was provided in two reports within the IPCC's sixth assessment cycle: first in SR1.5 in 2018 (Chap. 1 Sect. 1.2.1.3 and Fig. 1.2; Allen et al., 2018, summarised in the Summary for Policymakers (SPM) Sect. A.1 and Fig. SPM.1; IPCC, 2018) and second in AR6 in 2021 (WGI Chap. 3 Sect. 3.3.1.1.2 and Fig. 3.8; Eyring et al., 2021), summarised in the WGI Summary for Policymakers (SPM) Sect. A.1.3 and Fig. SPM.2; IPCC, 2021b) and quoted again without any updates in SYR (Sect. 2.1.1 and Fig. 2.1; IPCC, 2023a, and SYR Summary for Policymakers (SPM) Sect. A.1.2.; IPCC, 2023b).

8.1 Warming period definitions in the IPCC sixth assessment cycle

Temperature increases are defined relative to a baseline; IPCC assessments typically use the 1850–1900 average temperature as a proxy for the climate in pre-industrial times, referred to as the period before 1750, even though a small amount of warming likely occurred over 1750–1850 (see AR6 WGI Cross Chapter Box 1.2). Temperatures in the IPCC were reported as either global mean surface temperature (GMST) or GSAT; see Sect. S8.1 for details.

Tracking progress towards the long-term global goal to limit warming, in line with the Paris Agreement, requires the assessment of both what the current level of global surface temperatures is and whether a level of global warming, such as 1.5 °C, is being reached. Definitions for these were not specified in the Paris Agreement, and several ways of tracking levels of global warming are in use; here we focus on those adopted within AR6. When determining whether warming thresholds have been passed, both AR6 and SR1.5 adopted definitions that depend on future warming; in practice, levels of current warming were therefore reported in AR6 and SR1.5 using additional definitions that circumvented the need to wait for observations of the future climate, as described next. AR6 defined crossing time for a level of global warming as the midpoint of the first 20-year period during which the average *observed* warming for that period exceeds that level of warming (see AR6 WGI Chap. 2 Box 2.3) (the level of warming for a given year defined in this way is therefore not known until 10 years after that year). AR6 therefore reported current levels of both observed and *human-induced* warming as their averages over just the most recent 10 years (which gives warming that lags by only 5 years instead of 10 years) (see AR6 WGI Chap. 3 their Sect. 3.3.1.1.2); we refer to this definition as the "AR6 decade-average" warming. SR1.5 defined the level of warming in a given year as the average human-induced warming, in GMST, of a 30-year period centred on that year; when the given year is the *current* year, SR1.5 specified that the future 15 years (required for the mean) is revealed by extrapolating the multidecadal trend (see SR1.5 Chap. 1, their Sect. 1.2.1); we refer to this definition as the "SR1.5 trend-based" warming. If the multidecadal trend is interpreted as being linear (which it has been very close to over recent decades), this definition of current warming is equivalent to the endpoint of the trend line through the most recent 15 years of human-induced warming and therefore provides a definition of warming for the current year that depends only on historical warming. This interpretation produces results that in recent years have been identical (or extremely close) to the current annual-mean value of human-induced warming (see results in Sect. 8.2, and Sect. S8.3), so in practice the attribution assessment in SR1.5 was based not on the trend-based definition but on the simple annual-year attributed warming; we refer to this definition as the "SR1.5 annual-mean" warming. A diagram of these three definitions is given in Fig. S11.

8.2 Updated assessment approach of human-induced warming to date

This paper provides an update of the AR6 WGI and SR1.5 human-induced warming assessments including, for completeness, all three definitions (AR6 decade-average, SR1.5 trend-based single year, and SR1.5 annual-mean single year). The 2024 updates in this paper follow the same methods and process as the 2022 and 2023 updates provided in Forster et al. (2023, 2024). Global mean surface temperature (GMST) is adopted as the definition of global surface temperature (see Sect. S8.1). The three attribution methods used in AR6 are retained: the Global Warming Index (GWI) (building on Haustein et al., 2017), regularised optimal fingerprinting (ROF) (as in Gillett et al., 2021) and kriging for climate change (KCC) (Ribes et al., 2021). Details of each method, their different uses in SR1.5 and AR6, and any methodological changes, are provided in Sect. S8.2; method-specific results are also provided in Sect. S8.3. The overall estimate of attributed global warming for each definition (decade-average, trend-based and annual mean) is based on a multi-method assessment of the three attribution methods (GWI, KCC, ROF); the best estimate is given as the 0.01 °C-precision mean of the 50th percentiles from each method, and the *likely* range is given as the smallest 0.1 °C precision range that envelops the 5th to 95th percentile ranges of each method. This assessment approach is identical to last year's update (Forster et al., 2024); it is directly traceable to and fully consistent with the assessment approach in AR6, though it has been lightly extended in ways that are explained in Sect. S8.4.

Results are summarised in Table 6 and Fig. 9. Method-specific contributions to the assessment results, along with time series, are given in Sect. S8.3. Where results reported in GSAT differ from those reported in GMST (see Sect. S8.1), the additional GSAT results are given in Sect. S8.3.

The repeat calculations for attributable warming in 2010–2019 exhibit good correspondence with the results in AR6

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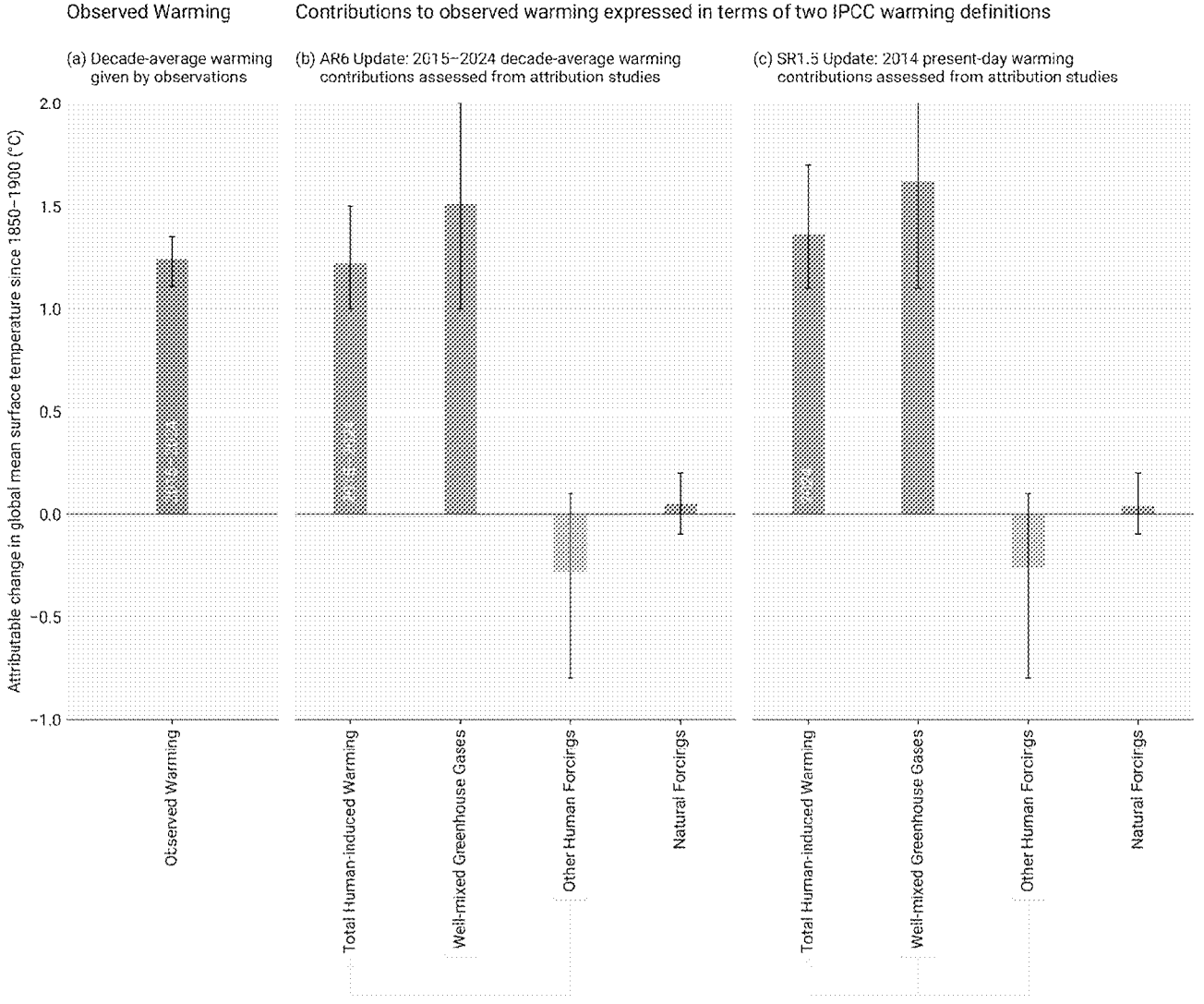

Figure 9. Updated assessed contributions to observed warming relative to 1850–1900; see AR6 WGI SPM.2. Results for all time periods in this figure are calculated using updated datasets and methods. The 2015–2024 average and 2024 results are this year's updated assessments for AR6 and SR1.5, respectively. Panel **(a)** shows updated observed global warming from Sect. 7, expressed as total global mean surface temperature (GMST), due to both anthropogenic and natural influences. Whiskers give the "very likely" range. Panels **(b)** and **(c)** show updated assessed contributions to warming, expressed as global mean surface temperature (GMST), from natural forcings and total human-induced forcings, which in turn consist of contributions from well-mixed GHGs and other human forcings. Whiskers give the "likely" range. Changes to warming levels since the IPCC sixth assessment cycle are depicted in Fig. S10.

WGI for the same period (see also Supplement, Sect. S8). The repeat calculation for the level of attributable anthropogenic warming in 2017 is about 0.1 °C larger than the estimate provided in SR1.5 for the same period, resulting from changes in methods and observational data (see AR6 WGI Chap. 2 Box 2.3). The updated results for warming contributions in 2024 are higher than in 2017, due also to 7 additional years of increasing anthropogenic forcing. Note also that the SR1.5 assessment only used the GWI method, whereas these annual updates apply the full AR6 multi-method assessment (see Sect. S8.4 for details and rationale).

In this 2025 update, we assess the 2015–2024 decade-average human-induced warming at 1.22 [1.0 to 1.5] °C, which is 0.15 °C above the AR6 assessment for 2010–2019. The single-year average human-induced warming is assessed to be 1.36 [1.1 to 1.7] °C in 2024 relative to 1850–1900. In general, these forced warming levels have evolved steadily and predictably in line with the current warming rate within uncertainty. The uncertainty range for the single-year level of anthropogenic warming already included 1.5 °C in previous years' assessments and for the first time this year also lies at the edge of the uncertainty range for the (lagged) decade mean definition. The single-year anthropogenic warming

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Table 6. Updates to assessments in the IPCC sixth assessment cycle of warming attributable to multiple influences. Estimates of warming attributable to multiple influences (in °C) relative to the 1850–1900 baseline period. Results are given as best estimates, with the likely range in brackets, and reported as global mean surface temperature (GMST). Results from the IPCC sixth assessment cycle, for both AR6 and SR1.5, are quoted in columns labelled (i) and are compared with repeat calculations in columns labelled (ii) for the same period using the updated methods and datasets to see how methodological and dataset updates alone would change previous assessments. Assessments for the updated periods are reported in columns labelled (iii).

Definition →	**(a)** IPCC AR6-attributable warming update			**(b)** IPCC SR1.5-attributable warming update		
	Value for decade (average of previous 10-year period)			Value for single year (30-year mean centred on current year)		
Period →	(i) 2010–2019 Quoted from AR6 Chap. 3 Sect. 3.3.1.1.2 Table 3.1 for attributed warming and Cross Chap. Box 2.3, Table 1 for observed warming	(ii) 2010–2019 Repeat calculation using the updated methods and datasets	(iii) 2015–2024 Updated value using updated methods and datasets	(i) 2017 Quoted from SR1.5, Chap. 1, Sect. 1.2.1.3	(ii) 2017 Repeat calculation using the updated methods and datasets	(iii) 2024 Updated value using updated methods and datasets
Component ↓						
Observed	1.06 [0.92 to 1.17]	1.07 [0.89 to 1.22]*	1.24 [1.11 to 1.35]*	–	–	1.52 [1.39 to 1.65]
Anthropogenic	1.07 [0.8 to 1.3]	1.09 [0.9 to 1.3]	1.22 [1.0 to 1.5]	1.0 [0.8 to 1.2]***	1.13 [0.9 to 1.3]	1.36 [1.1 to 1.7]
Well-mixed GHGs	1.40** [1.0 to 2.0]	1.40 [1.0 to 1.9]	1.51 [1.0 to 2.0]	NA	1.45 [1.0 to 1.9]	1.62 [1.1 to 2.1]
Other human forcings	−0.32** [−0.8 to 0.0]	−0.30 [−0.8 to 0.1]	−0.28 [−0.8 to 0.1]	NA	−0.31 [−0.8 to 0.1]	−0.26 [−0.8 to 0.1]
Natural forcings	0.03** [−0.1 to 0.1]	0.05 [−0.1 to 0.2]	0.05 [−0.1 to 0.2]	NA	0.05 [−0.1 to 0.2]	0.04 [−0.1 to 0.2]

* Updated GMST observations, quoted from Sect. 7 of this update, are marked with an asterisk, with "very likely" ranges given in brackets. ** In AR6 WGI, best-estimate values were not provided for warming attributable to well-mixed GHGs, other human forcings and natural forcings (though they did receive a "likely" range); for comparison, best estimates (marked with two asterisks) have been retrospectively calculated in an identical way to the best estimate that AR6 provided for anthropogenic warming (see discussion in Supplement Sect. S8.4.1). *** The SR1.5 assessment drew only on GWI rounded to 0.1 °C precision, whereas the repeat and updated calculations use the updated multi-method assessment approach. NA: not available.

best estimate is well below the observed best estimate for 2024 (1.52 °C; see Sect. 7), but note that the best estimate and lower uncertainty for observed warming lie within the uncertainty for single-year anthropogenic warming from each of the three attribution methods (see Table S5), whereas the upper uncertainty range of observed warming lies above the range for anthropogenic warming for the two attribution methods that fully exclude internal variability.

The best estimates for decade-average and single-year human-induced warming are 0.04 and 0.05 °C respectively above the value estimated in the previous update for the year 2023 (Forster et al., 2024) but should not be interpreted as a substantive increase in the rate of forced anthropogenic warming, as the rate increase is well within uncertainty ranges (Sect. 8.3).

AR6 found that, averaged for the 2010–2019 period, essentially all observed global surface temperature change was human-induced, with solar and volcanic drivers and internal climate variability making a negligible contribution. This conclusion remains the same for the 2015–2024 period. Generally, whatever methodology is used, on a global scale, the best estimate of the current level of human-induced warming is (within uncertainty) similar to the observed global surface temperature change (Table 6).

8.3 Rate of human-induced global warming

Estimates of the human-induced warming rate follow the same methodology as in the previous year's update (a rolling 10-year linear trend in attributed anthropogenic warming). A full description of the approach can be found in Sect. S8.5. The rate of increase in attributed anthropogenic warming over time is distinct from the rate of increase in the observed global surface temperature, which is also affected by internal variability such as El Niño and natural forcings such as volcanic activity (see discussions in Sect. 7.2). The rate of anthropogenic warming we estimate here is driven by the rate of change of anthropogenic ERF (Sect. 5), with variations in the climate forcing trend over time correlating with variations in the rate of attributed warming (Fig. 10).

Estimates for the trend derived from the three warming attribution methodologies are presented in Table 7, with results for individual attribution methods detailed in Table S6. The GWI (based on observed warming and forcing) and KCC (based on CMIP simulations) methodologies report results that are in close agreement, while estimates derived with the ROF method (also based on CMIP simulations) are more strongly influenced by residual internal variability that remains in the anthropogenic warming signal due to the limitations in size of the available CMIP ensemble. The median result is presented at a precision of 0.01 °C per decade for the overall multi-method rate of warming assessment.

An overall best estimate attributed rate of human-induced warming of 0.27 °C per decade is found for the decade 2015–2024. This increased rate relative to the AR6 assessment of 0.2 °C per decade is broken down in the following way: (i) 0.03 °C per decade from changing the rounding precision (updating the AR6 2010–2019 warming rate assessment from 0.2 to 0.23 °C per decade); (ii) 0.03 °C per decade from methodological and dataset updates (updating the 2010–2019 warming rate from 0.23 °C per decade to 0.26 °C per decade, including the effect of adding 5 additional observed years to the attribution over the entire historical period); and (iii) 0.01 °C per decade due to a real increase in rate for

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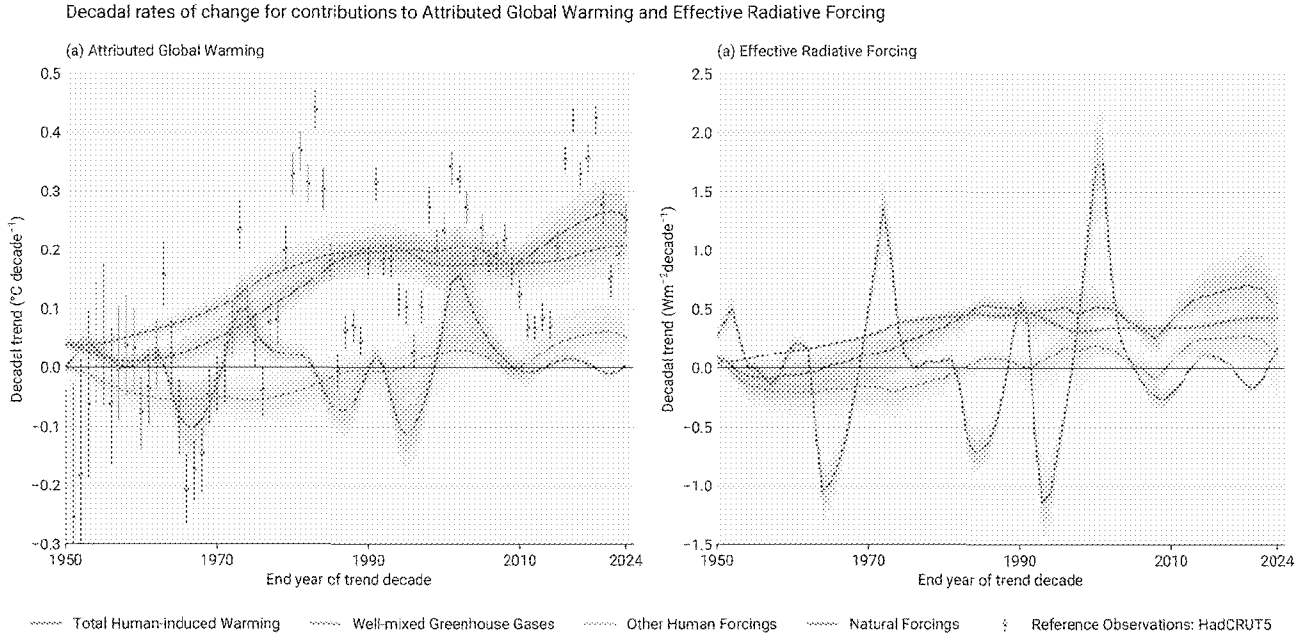

Figure 10. Rates of **(a)** attributable warming (global mean surface temperature (GMST)) and **(b)** effective radiative forcing. The attributable warming rate time series are calculated using the Global Warming Index method with full ensemble uncertainty. The observed GMST rates included for reference are also calculated with uncertainty from the HadCRUT5 ensemble and, for consistency with the attributed warming rates, do not include standard regression error, which, for observed warming, would increase the size of the error bars. The effective radiative forcing rates are calculated using a representative 1000-member ensemble of the forcings provided in Sect. 5 of this paper. The depicted rates are the decadal rates, with the end year of the decade in question being the value given on the time axis.

the 2015–2024 period since the 2010–2019 period (updating 0.26 °C per decade for 2010–2019 to 0.27 °C per decade for 2015–2024), consistent with increased GHG emissions over the last decade. The spread of rates across the three attribution methods remains similar to their spread in AR6, and previous updates of this work, and hence does not support a decrease in the headline uncertainty range. However, as previous assessments suggested, we update the uncertainty range for the rate of human-induced warming from [0.1–0.3] °C per decade in AR6 to [0.2–0.4] °C per decade to better reflect the closer agreement of the 5 % floors and the larger spread in the 95 % ceilings of the three methods and higher rate from the ROF method. The rate of human-induced warming for the 2015–2024 decade is concluded to be 0.27 °C per decade with a range of [0.2–0.4] °C per decade). This agrees with the decadal trend in observed warming of 0.26 °C per decade (also calculated as a linear trend through 10-year periods – see Sect. 7.1). It is important to note, however, that internal variability leads to the decadal rates of observed warming being far less stable than for anthropogenic warming, and the very close correspondence between the two this year is somewhat incidental (see Fig. 10).

9 Remaining carbon budget

AR5 (IPCC, 2013) assessed that long-term global surface temperature increase caused by CO_2 emissions is close to linearly proportional to the total amount of cumulative CO_2 emissions (Collins et al., 2013). The most recent AR6 report reaffirmed this assessment and highlights that this near-linear relationship also holds between cumulative CO_2 emissions and maximum global surface temperature increase caused by CO_2 (Canadell et al., 2021). This near-linear relationship implies that for keeping global warming below a specified temperature level, one can estimate the total amount of CO_2 that can ever be emitted. When expressed relative to a recent reference period, this is referred to as the remaining carbon budget (Rogelj et al., 2018).

AR6 assessed the remaining carbon budget (RCB) in Chap. 5 of its WGI report (Canadell et al., 2021) for warming limits ranging from 1.3 to 2.4 °C relative to the 1850–1900 period (see Table 5.8 in Canadell et al., 2021). A selection of these (1.5, 1.7 and 2 °C) were also reported in its Summary for Policymakers (Table SPM.2, IPCC, 2021b). These RCB values are updated in this section using the same method as last year (Forster et al., 2024). Data for four warming limits (1.5, 1.6, 1.7 and 2 °C) are included in Table 8, while figures for more values are included in Sect. S9.

The RCB is estimated by application of the WGI AR6 method described in Rogelj et al. (2019), which involves

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Table 7. Updates to the IPCC AR6 rate of human-induced warming. Results for each method are given in the Table S6; assessment results are given as a best estimate with likely range in brackets. Results from AR6 WGI (Chap. 3 Sect. 3.3.1.1.2 Table 3.1) are quoted in column (i) and compared with a repeat calculation using the updated methods and datasets in column (ii) and finally updated for the 2015–2024 period in column (iii). The AR6 assessment result was identical to the SR1.5 assessment result, though the latter was based on a different set of studies and time frames.

Definition →	IPCC AR6 anthropogenic warming rate update Linear trend in anthropogenic warming over the trailing 10-year period		
Period →	(i) 2010–2019 Quoted from AR6 Chap. 3 Sect. 3.3.1.1.2 Table 3.1	(ii) 2010–2019 Repeat calculation using the updated methods and datasets	(iii) 2015–2024 Updated value using updated methods and datasets
Anthropogenic warming rate assessment	Quoted from AR6: 0.2 [0.1 to 0.3] Using the median approach: 0.23 [0.1 to 0.3]*	0.26 [0.2 to 0.4]	0.27 [0.2 to 0.4]
Observed		0.37	0.26

* Note that for clarity and ease of comparison with this year's updated assessment, the assessed rate in column (i) both quotes the assessment from AR6 and retrospectively applies the median approach adopted in this paper. The observed rates are calculated using the multi-dataset observed temperature dataset from Sect. 7; no ensemble is available for this, hence the absence of an uncertainty range.

the combination of the assessment of five factors: (i) the amount of human-induced warming for the most recent decade (given in Sect. 8); (ii) the transient climate response to cumulative emissions of CO_2 (TCRE), which quantifies the linear proportionality between cumulative CO_2 emissions and CO_2-induced warming; (iii) the zero emissions commitment (ZEC), representing the expected amount of additional (at present unrealised) warming caused by past CO_2 emissions; (iv) the temperature contribution of future non-CO_2 emissions; and (v) an adjustment term for Earth system feedbacks that are otherwise not captured through the other factors. AR6 WGI reassessed all five terms (Canadell et al., 2021). Lamboll et al. (2023) further considered the temperature contribution of non-CO_2 emissions and integrated different uncertainties, while Rogelj and Lamboll (2024) clarified the reductions in non-CO_2 emissions that are assumed in the RCB estimation.

The RCB for 1.5, 1.6, 1.7 and 2 °C warming levels is reassessed based on the most recent available data. Estimated RCBs are reported in Table 8. They are expressed relative to the start of 2025 for estimates based on the 2015–2024 human-induced warming update (Sect. 8). Based on the variation in non-CO_2 emissions across the scenarios in AR6 WGIII scenario database, the estimated RCB values can be higher or lower by around 200 Gt CO_2 depending on how successful non-CO_2 emissions reductions are (Lamboll et al., 2023; Rogelj and Lamboll, 2024). Notably, RCB estimates consider the subset of non-CO_2 emission scenarios in the AR6 WGIII database that are aligned with a global transition to net zero CO_2 emissions (Lamboll et al., 2023; Rogelj and Lamboll, 2024). These estimates assume median reductions in non-CO_2 emissions between 2020–2050 of CH_4 (about 50 %), N_2O (about 20 %) and SO_2 (about 80 %) (see Supplement, Sect. S9 and Table S7, and Rogelj and Lamboll, 2024). If these non-CO_2 GHG emission reductions are not achieved, the RCB for all temperature targets would be smaller than the values reported here in Table 8 (see Lamboll et al., 2023; Rogelj and Lamboll, 2024).

Compared to RCB values reported in AR6, our estimates here are smaller, owing to several factors. First, AR6 budgets were expressed from 2020 onwards, and approximately 200 Gt CO_2 was emitted between 2020 and 2024. Second, we use updated physical models of non-CO_2 forcing, which leads to an increased estimate of the importance of aerosols that are expected to decline with time in low emissions pathways (Rogelj et al., 2014; Rogelj and Lamboll, 2024). This decreased negative forcing from aerosols is expected to cause additional net non-CO_2 warming because more non-CO_2 GHG warming is being unmasked, and this decreases the RCB (Lamboll et al., 2023) by slightly over 100 Gt CO_2. There was also a small reduction in the budget (about 10 Gt CO_2) from using the newer AR6 scenario set. Finally, the updated warming estimate reported in Sect. 8 is slightly increased due to the high observed temperatures in the last few years, which resulted in a further reduction of the budget by around 40 Gt CO_2, relative to values reported in last year's assessment (Forster et al., 2024). This gives a total reduction in RCB values estimated from the beginning of 2025 of $\sim$ 370 Gt CO_2 compared to the values from 2020 reported in AR6.

This year's update of the 1.5 °C budget uses the historical warming level for the 2015–2024 period of 1.24 °C, with 0.11 °C future contribution of non-CO_2 warming. Assuming a median TCRE estimate of 0.45 °C per 1000 Gt CO_2, this

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Table 8. Updated estimates of the remaining carbon budget for 1.5, 1.6, 1.7 and 2.0 °C, for five levels of likelihood, considering only uncertainty in TCRE. Estimates are expressed relative to the start of 2024. The probability includes only the uncertainty in how the Earth immediately responds to CO_2 emissions (TCRE), not long-term committed warming or uncertainty in the climate response to other non-CO_2 emissions. All values are rounded to the nearest 10 Gt CO_2. Additional values can be found in Tables S7 and S8.

Temperature (°C)	Estimated remaining carbon budgets from the beginning of 2025 (Gt CO_2)				
Avoidance probability:	17 %	33 %	50 %	67 %	83 %
1.5	320	200	130	80	30
1.6	620	420	310	240	160
1.7	910	640	490	390	290
2.0	1790	1310	1050	870	690

gives around 340 Gt CO_2 from the midpoint of the period, from which we subtract around 210 Gt CO_2 (204 Gt CO_2 that was already emitted from the middle until the end of the 2015–2024 period and 7 Gt CO_2 that represents the median estimate of the impact of Earth system feedbacks such as permafrost feedback that would otherwise not be covered). The same method is used to calculate budgets for the other warming levels.

The values in Table 8 are all greater than zero, implying that we have not yet emitted the amount of CO_2 that would commit us to these levels of warming. However, including the uncertainty in ZEC (as in Table S8), non-CO_2 emission and forcing uncertainty, and underrepresented Earth system feedbacks results in negative RCB estimates for limiting warming to low temperature limits with high likelihood. A negative RCB for a specific temperature limit would mean that the world is already committed to this amount of warming and that net negative emissions would therefore be required to return to the temperature limit after a period of overshoot. The assumption behind such a calculation is that we can treat the warming impact of positive and negative net emissions as approximately symmetric. While the claim of symmetry is likely valid for small emissions values, some model studies have shown that it holds less well for reversal of larger emissions (Canadell et al., 2021; Zickfeld et al., 2021; Vakilifard et al., 2022; Pelz et al., 2025). As such, larger exceedances of the RCB for a particular temperature target would decrease the likelihood that the temperature target could still be achieved by an equivalent amount of net negative emissions.

Note that the 50 % RCB estimate of 130 Gt CO_2 would be exhausted in a little more than 3 years if global CO_2 emissions remain at 2024 levels (42 Gt CO_2 yr^{-1}; see Table 1). This is not expected to correspond exactly to the time that 1.5 °C global warming level is reached due to uncertainty associated with committed warming from past CO_2 emissions (the ZEC) as well as ongoing warming and cooling contributions from non-CO_2 emissions. For comparison, our estimate of 2024 anthropogenic warming (1.36 °C) and the recent rate of increase (0.27 °C per decade) would suggest that continued emissions at current levels would cause human-induced global warming to reach 1.5 °C in approximately 5 years.

10 Indicator of climate and weather extremes: land average maximum temperatures

Changes in climate and weather extremes are among the most visible effects of human-induced climate change. Within AR6 WGI, a full chapter was dedicated to the assessment of past and projected changes in extremes on continents (Seneviratne et al., 2021), and the chapter on ocean, cryosphere and sea-level changes also provided assessments on changes in marine heatwaves (Fox-Kemper et al., 2021). Global indicators related to climate extremes include averaged changes in climate extremes, for example, the mean increase in annual minimum and maximum temperatures on land (AR6 WGI Chap. 11, Fig. 11.2, Seneviratne et al., 2021) or the area affected by certain types of extremes (AR6 WGI Chap. 11, Box 11.1, Fig. 1, Seneviratne et al., 2021; Sippel et al., 2015).

The presented climate indicator for changes in temperature extremes consists of land average maximum temperatures for any single day in a year (TXx) (excluding Antarctica). Figure 11 updates the land mean TXx shown in Forster et al. (2023, 2024), originally based on Fig. 11.2 from Seneviratne et al. (2021). Three datasets are analysed: HadEX3 (Dunn et al., 2020), Berkeley Earth Surface Temperature (building off Rohde et al., 2013), and the fifth-generation ECMWF atmospheric reanalysis of the global climate (ERA5; Hersbach et al., 2020). HadEX3 is static and has not received any updates. Berkeley Earth has been extended and updated compared to Forster et al. (2024), resulting in TXx differences for most years (less than 0.1 °C), and now includes data for 2023. Of the three datasets, only ERA5 covers the whole of 2024 at the present time. TXx is calculated by averaging the annual maximum temperature over all available land grid points (excluding Antarctica) and then converting this into anomalies with respect to a base period of 1961–1990. To express the TXx as anomalies with respect to 1850–1900, we add an offset of 0.51 °C to all three datasets. See Sect. S10 for details on the data selection, averaging and offset computation.

Our climate has warmed rapidly in the last few decades (Sect. 7), which also manifests in changes in the occurrence and intensity of climate and weather extremes. From about 1980 onwards, all datasets point to a strong TXx increase, which coincides with the transition from global dimming, associated with aerosol increases, to brightening, associated with aerosol decreases (Wild et al., 2005, Sect. 4). The ERA5-based TXx warming estimate with respect to

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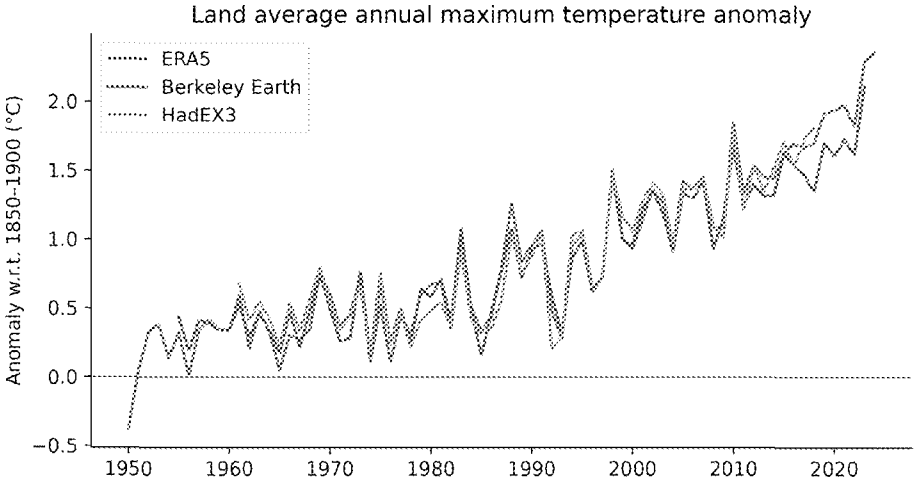

Figure 11. Time series of observed temperature anomalies for land average annual maximum temperature (TXx) for ERA5 (1950–2024), Berkeley Earth (1955–2023) and HadEX3 (1961–2018), with respect to 1850–1900. The datasets have different spatial coverage and are not coverage-matched. All anomalies are calculated relative to 1961–1990, and an offset of 0.51 °C is added to obtain TXx values relative to 1850–1900. Note that while the HadEX3 numbers are the same as shown in Seneviratne et al. (2021) Fig. 11.2, these numbers were not specifically assessed.

Table 9. Anomalies of land average annual maximum temperature (TXx) for recent decades based on HadEX3, Berkeley Earth and ERA5, with respect to 1850–1900. All anomalies are calculated relative to 1961–1990, and an offset of 0.51 °C is added to obtain TXx values relative to 1850–1900.

	HadEX3	Berkeley Earth	ERA5
2000–2009	1.23	1.18	1.21
2005–2014	1.37	1.31	1.4
2009–2018	1.52	1.41	1.54
2011–2020	–	1.45	1.63
2013–2022	–	1.52	1.72
2014–2023	–	1.6	1.81
2015–2024	–	–	1.9

1850–1900 for 2024 is at 2.35 °C, an increase of 0.05 °C compared to 2023 and thus even warmer than the previous record in 2023. On longer timescales, land average TXx has warmed 0.49 °C in the past 10 years (comparing the decades 2015–2024 to 2005–2014) and 1.90 °C with respect to pre-industrial conditions (Table 9). Since the offset relative to our pre-industrial baseline period is calculated over 1961–1990, temperature anomalies align by construction over this period but can diverge afterwards.

11 Global land precipitation

Anthropogenic radiative forcings modify the Earth's energy budget and subsequently drive substantial and widespread changes in the global water cycle including precipitation, evaporation, atmospheric moisture and runoff (Forster et al., 2021, Douville et al., 2021; Gulev et al. 2021). AR6 Chap. 8 assessed that human-caused climate change has driven detectable changes in the global water cycle since the mid-20th century with high confidence, including an overall increase in atmospheric moisture (7 % per 1 °C of warming), precipitation intensity (1 %–3 % per 1 °C of warming) and increased terrestrial evapotranspiration (Douville et al., 2021).

In AR6, global land precipitation was highlighted as one of the large-scale indicators of climate change rather than global precipitation since land precipitation has greater societal relevance, and in situ precipitation records over land extend back to the early to mid-20th century quasi-globally except Antarctica and parts of Africa and South America (Gulev et al., 2021; Lee et al., 2021; Douville et al., 2021). AR6 assessed that global land precipitation has likely increased since the middle of the 20th century with a faster increase since the 1980s with large interannual variability and regional heterogeneity. The observed northern hemispheric land summer monsoon precipitation experienced a significant decline during 1901–2014, which has been attributed to the dominant influence of anthropogenic aerosols (Cao et al., 2022). Here, we include an update of global land precipitation change since AR6 (i.e. from 2020 to 2024).

Figure 12 shows the annual global land precipitation anomaly relative to 1991–2020, following the current WMO climatology reference, obtained from GPCC V2020 (Schamm et al., 2014), CRU TS 4.08 (Harris et al., 2020), GPCP V.2.3 (Adler et al., 2018) and GHCN V4 (Menne et al., 2018) observed datasets. The change of reference period to 1991–2020 affects the perceived evolution compared to Fig. 2.15c in AR6 WGI, which had a 1981–2010 reference period. There is little consistency among datasets due to differences in input data, completeness of records, period

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of covered and the gridding procedures applied (Sun et al., 2018; Nogueira, 2020). While the globally averaged land surface specific humidity has continuously increased (Dunn et al., 2024), global land precipitation has exhibited considerable interannual to interdecadal variability (Fig. 12). There was a positive anomaly in global land precipitation in 2024 but a negative anomaly in 2023. The former was contributed to by above-normal precipitation over the Asian and Australian monsoon region, likely associated with La Niña conditions, but was offset by dry conditions over South America and the southern part of Africa. The latter was driven by below-normal precipitation over South Asia, the Maritime Continent, the southern part of North America and the northern part of South America, due to El Niño conditions, with a corresponding increase in precipitation over the ocean (Adler and Gu, 2024).

12 Global mean sea-level rise

Global mean sea-level rise (GMSLR) is included in this annual update of AR6 for the first time. GMSLR is primarily driven by (i) thermal expansion as the ocean warms and (ii) increases in ocean mass associated with the addition of water or ice from land-based reservoirs, including glaciers and ice sheets (Fox-Kemper et al., 2021). Most of these processes are directly linked to changes in the global Earth energy inventory (Sect. 6). Sea-level rise can have large consequences for coastal ecosystems, safety and management, as it increases the baseline for sea-level extremes arising from short-term phenomena such as storm surges, waves and tides.

Observed GMSLR was assessed in IPCC AR6 WG1, in Chap. 2 (their Sect. 2.3.3.3, Gulev et al., 2021) and Chap. 9 (their Sect. 9.6.1 and Cross-Chapter Box 9.1, Fox-Kemper et al., 2021), on the basis of tide gauge reconstructions (up to 1993) and satellite altimeter observations (1993–2018). The assessment of GMSLR from tide gauge reconstructions used the ensemble approach presented by Palmer et al. (2021), which quantifies an ensemble and its uncertainties by combining an estimate of the structural uncertainty (informed by the ensemble spread) with an estimate of the internal uncertainty across the ensemble (i.e. the parametric uncertainty of each of the members in the ensemble). The members included in the tide gauge ensemble, which informed the total sea-level change estimate for the period 1901–1992, were reconstructions from Church et al. (2011), Dangendorf et al. (2019), Frederikse et al. (2020), and Hay et al. (2015). For the satellite period, from 1993 to 2018, AR6 used the estimate of the WCRP Global Sea Level Budget Group (2018), which was constructed from satellite-based GMSLR time series from six groups (AVISO/CNES, CSIRO, NASA/GSFC, NOAA, SL_cci/ESA and University of Colorado). Based on this information, AR6 concluded that GMSLR increased by 0.20 [0.15 to 0.25] m over the period 1901 to 2018, with a rate of 1.73 [1.28 to 2.17] mm yr^{-1} (*high confidence*). Periods closer to the present showed an accelerating GMSLR, with a rate of 2.3 [1.6 to 3.1] mm yr^{-1} over the period 1971–2018 increasing to 3.7 [3.2 to 4.2] mm yr^{-1} over the period 2006–2018 (high confidence).

Here, we extend the AR6 GMSLR time series, which ended in 2018, closer to the present day. We use the same tide-gauge-based ensemble estimate as in AR6 for the period up to 1993. We do note that two new reconstructions have been published recently, both providing rates in line with the AR6 assessment rates given above. The new GMSLR reconstruction by Dangendorf et al. (2024) uses a Kalman smoother and adjusted estimates of the contributions of glacial isostatic adjustment and barystatic and sterodynamic changes to sea-level change and finds a trend of 1.50 ± 0.20 mm yr^{-1} for the period 1900–2021. The new reconstruction by Wang et al. (2024) uses an updated vertical land motion correction and considers barystatic fingerprints and sterodynamic patterns from CMIP6 models and finds a trend of 1.6 ± 0.2 mm yr^{-1} over 1900–2019.

The satellite record now provides observations up to the end of 2024, for three out of the six satellite data products used for the WCRP estimate used in AR6. The three records available to the end of 2024 are from NASA (2025), NOAA (2025) and AVISO (2025). All data were downloaded on 19 February 2025. We use the global mean time series based on the reference missions, with seasonal signals removed and corrected for glacial isostatic adjustment. We first compute annual averages and then an ensemble average time series, which is spliced to the AR6 GMSLR record ending in 2018. For consistency, we retain the uncertainties from the six-member WCRP ensemble and propagate them over the period 2019–2024. We note that reprocessing of the altimetry record is periodically required to account for new insights on instrument drift, retracking and geophysical corrections to the altimetry missions. This reprocessing may lead to small differences in the satellite altimeter record and the associated assessment of GMSLR in future iterations of IGCC.

Over the period 2019 to 2024, global mean sea level has increased by 26.1 [19.8 to 32.4] mm. When combining the AR6 estimate up to 2018 with the satellite time series for 2019–2024, we find a total GMSLR of 228.0 [176.4 to 279.6] mm for the period 1901–2024, which translates to an average rate of 1.85 [1.43 to 2.27] mm yr^{-1} (Table 10, Fig. 13). The rate increase associated with extending the time series by just 6 years, as well as the increasing rates over consecutive 20-year periods (Fig. 13b), indicates a continuing acceleration of GMSLR. This is in line with the assessments of AR6 (Fox-Kemper et al., 2021), SROCC (Oppenheimer et al., 2019) and AR5 (Church et al., 2013) that sea-level change has been accelerating over the course of the 20th and early 21st centuries and consistent with the observed acceleration in some components of the Earth heat inventory (see Sect. 6).

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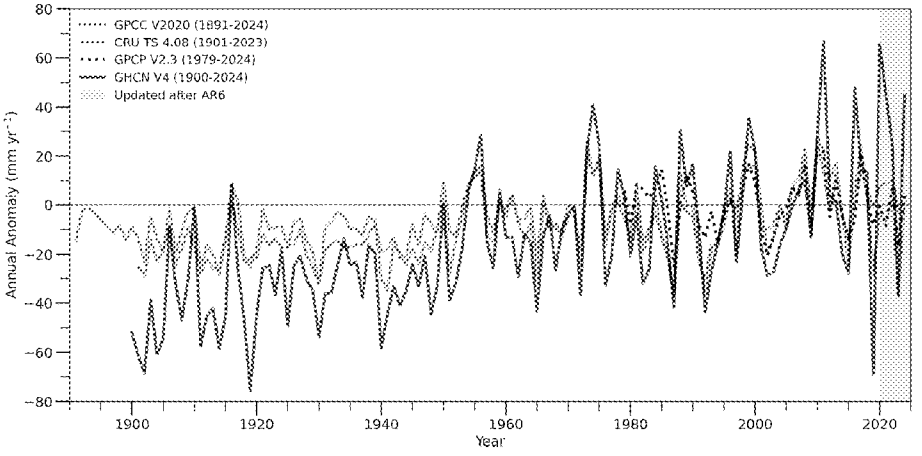

Figure 12. Time series of annual global land precipitation (mm yr^{-1}) from 1891 to date relative to a 1991–2020 climatology obtained from GPCP V2020, CRU TS 4.08, GPCP V2.3 and GHCN V4 (note that different products commence at distinct times). Annual global land precipitation for each observed data is estimated following the AR6 method except the period of climatology and updated from 2020 to 2024. In AR6, the reference period of the climatology was from 1981 to 2010.

Table 10. Observed global mean sea-level rise (GMSLR) as presented in IPCC AR6, Table 9.5 (Fox-Kemper et al., 2021), compared with the extended time series in this study. Values are expressed as the total change (Δ) in the annual mean over each period (mm), along with the equivalent rate calculated as the total change divided by the number of years (mm yr^{-1}). Uncertainties represent the very likely range.

Observed GMSLR		IPCC AR6	This study
Start year		End year 2018	End year 2024
1901	Δ (mm)	201.9 [150.3 to 253.5]	228.0 [176.4 to 279.6]
	mm yr^{-1}	1.73 [1.28 to 2.17]	1.85 [1.43 to 2.27]
1971	Δ (mm)	109.6 [72.8 to 146.4]	135.8 [99.0 to 172.5]
	mm yr^{-1}	2.33 [1.55 to 3.12]	2.56 [1.87 to 3.26]
1993	Δ (mm)	81.2 [72.1 to 90.2]	107.3 [98.2 to 116.4]
	mm yr^{-1}	3.25 [2.88 to 3.61]	3.46 [3.17 to 3.75]
2006	Δ (mm)	44.3 [38.6 to 50.0]	70.4 [64.7 to 76.1]
	mm yr^{-1}	3.69 [3.21 to 4.17]	3.91 [3.59 to 4.23]

13 Code and data availability

We have published a set of selected key indicators of global climate change via Climate Change Tracker (https://climatechangetracker.org/, Climate Change Tracker, 2025), a platform which aims to provide reliable, user-friendly, high-quality interactive dashboards, visualisations, data, and easily accessible insights of this paper.

With Climate Change Tracker we aim to reach a wider public audience, including policymakers involved in UNFCCC negotiations and decision-makers working in climate change mitigation and adaptation. Climate Change Tracker plans to update significant indicators multiple times throughout the year, providing an up-to-date picture of the indicators of climate change. Within the dashboards, all data are traceable to the underlying sources. Figure 14 presents a screenshot of the IGCC dashboard.

The carbon budget calculation is available from https://github.com/Rlamboll/AR6CarbonBudgetCalc/tree/v1.0.3 (Lamboll and Rogelj, 2025). The code and data used to produce other indicators are available in repositories under https://github.com/ClimateIndicator/data/tree/v2025.06.11 (Smith et al., 2025b). All data are available from https://doi.org/10.5281/zenodo.15639576 (Smith et al., 2025a). Data are provided under the CC-BY 4.0 License.

HadEX3 [3.0.4] data were obtained from https://catalogue.ceda.ac.uk/uuid/115d5e4ebf7148ec941423ec86fa9f26 (Dunn et al., 2023) on 5 April 2023 and are © British Crown Copyright, Met Office 2022, provided under an Open Government Licence; http://www.nationalarchives.gov.uk/doc/open-government-licence/version/2/ (last access: 2 June 2023).

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Table 11. Summary of headline results and methodological updates from the Indicators of Global Climate Change (IGCC) initiative.

Climate indicator	AR6 2021 assessment	This 2024 assessment	Explanation of changes	Methodological updates since AR6
GHG emissions AR6 WGIII Chap. 2: Dhakal et al. (2022); see also Minx et al. (2021)	2010–2019 average: 55.9 ± 6 Gt CO_2e	2010–2019 average: 52.9 ± 5.4 Gt CO_2e 2014–2023 average: 53.6 ± 5.2 Gt CO_2e	Average emissions in the past decade grew at a slower rate than in the previous decade. The change from AR6 is due to a systematic downward revision in CO_2-LULUCF and CH_4 estimates. Real-world emissions have slightly increased.	CO_2-LULUCF emissions revised down. CO_2 GCB fossil fuel and industry emissions used instead of EDGAR. PRIMAP-hist TP used in place of EDGAR for CH_4 and N_2O emissions and atmospheric measurements taken for F-gas emissions. These changes reduce estimates by around 3 Gt CO_2e (Sect. 2).
GHG concentrations AR6 WGI Chap. 2: Gulev et al. (2021)	2019: CO_2, 410.1 [±0.36] ppm CH_4, 1866.3 [±3.2] ppb N_2O, 332.1 [±0.7] ppb	2024: CO_2, 422.8 [±0.4] ppm CH_4, 1929.7 [±3.3] ppb N_2O, 337.9 [±0.4] ppb	Increases caused by continued GHG anthropogenic emissions	Updates based on NOAA data and AGAGE (Sect. 3)
Effective radiative forcing change since 1750 AR6 WGI Chap. 7: Forster et al. (2021)	2019: 2.72 [1.96 to 3.48] W m^{-2}	2024: 2.97 [2.05 to 3.77] W m^{-2}	Trend since 2019 is caused by increases in GHG concentrations and reductions in aerosol precursors.	Follows AR6 with minor update to aerosol precursor treatment and emissions dataset that revises 2019 ERF estimate relative to 1750 downwards (more negative) by 0.09 W m^{-2}. Added this year is a new method to estimate the ERF from land-use surface reflection and irrigation to avoid scaling with cumulative emissions. This does not materially affect the ERF (Sect. 5).
Earth's energy imbalance AR6 WGI Chap. 7: Forster et al. (2021)	2006–2018 average: 0.79 [0.52 to 1.06] W m^{-2}	2012–2024 average: 0.99 [0.70 to 1.28] W m^{-2}	A 25 % increase in energy imbalance estimated based on increased rate of ocean heating.	Ocean heat content time series extended from 2018 to 2024 using all five of the AR6 datasets. Other heat inventory terms updated following von Schuckmann et al. (2023). Ocean heat content uncertainty is used as a proxy for total uncertainty. Further details in Sect. 6.
Global mean surface temperature change since 1850–1900 AR6 WGI Chap. 2: Gulev et al. (2021)	2011–2020 average: 1.09 [0.95 to 1.20] °C	2015–2024 average: 1.24 [1.11 to 1.35] °C	An increase of 0.15 °C within 4 years, indicating a high decadal rate of change which may in part be internal variability.	Methods match four datasets used in AR6. Individual datasets have updated historical data, but these changes are not materially affecting results (Sect. 7).
Human-induced global warming since pre-industrial levels AR6 WGI Chap. 3: Eyring et al. (2021) SR1.5 Chap. 1	2010–2019 decade average: 1.07 [0.8 to 1.3] °C 2017 single year: 1.0 [0.8 to 1.2] °C	2015–2024 decade average: 1.22 [1.0 to 1.5] °C 2024 single year: 1.36 [1.1 to 1.7] °C	An increase of 0.15 °C within 5 years, indicating a high decadal rate of change (broadly consistent with warming projections). The decadal warming rate increased slightly between 2019 and 2024. One of the three AR6 methods is diverging.	The three methods for the basis of the AR6 assessment are retained, but each has new input data (Sect. 8).
Remaining carbon budget for 50 % likelihood of limiting global warming to 1.5 °C AR6 WGI Chap. 5: Canadell et al. (2021)	From the start of 2020: 500 Gt CO_2	From the start of 2025: 130 Gt CO_2	The 1.5 °C budget is becoming very small. The RCB can exhaust before the 1.5 °C threshold is reached due to having to allow for future non-CO_2 warming.	Emulator and scenario change has reduced budget since 2020 by 100 Gt CO_2 (Sect. 9).
Land average maximum temperature change compared to pre-industrial times. AR6 WGI Chap. 11: Seneviratne et al. (2021)	2009–2018 average: 1.55 °C	2015–2024 average: 1.90 °C	Rising at a substantially faster rate compared to global mean surface temperature	HadEX3 data used in AR6 replaced with ERA reanalysis data employed in this report, which is more updatable going forward. Adds 0.01 °C to estimate (Sect. 10)
Global land precipitation compared to pre-industrial times (Douville et al., 2021)	Likely increased since the middle of the 20th century with a faster increase since the 1980s with large interannual variability	Large interannual variability associated with El Niño dominates the record in recent years, making long-term trend less clear	2023 exhibited a negative anomaly relative to pre-industrial times due to El Niño conditions	The four datasets used in AR6 have been extended (Sect. 11)
Global mean sea-level rise since 1901 (Gulev et al., 2021; Fox-Kemper et al., 2021)	1901 to 2018 change 201.9 [150.3 to 253.5] mm at a rate of 1.73 [1.28 to 2.17] mm yr^{-1}	1901 to 2024 change 228.0 [176.4 to 279.6] mm at a rate of 1.85 [1.43 to 2.27] mm yr^{-1}	Sea-level rise continues to accelerate.	AR6 data extended with three of the six datasets from AR6, using latest satellite data (Sect. 12).

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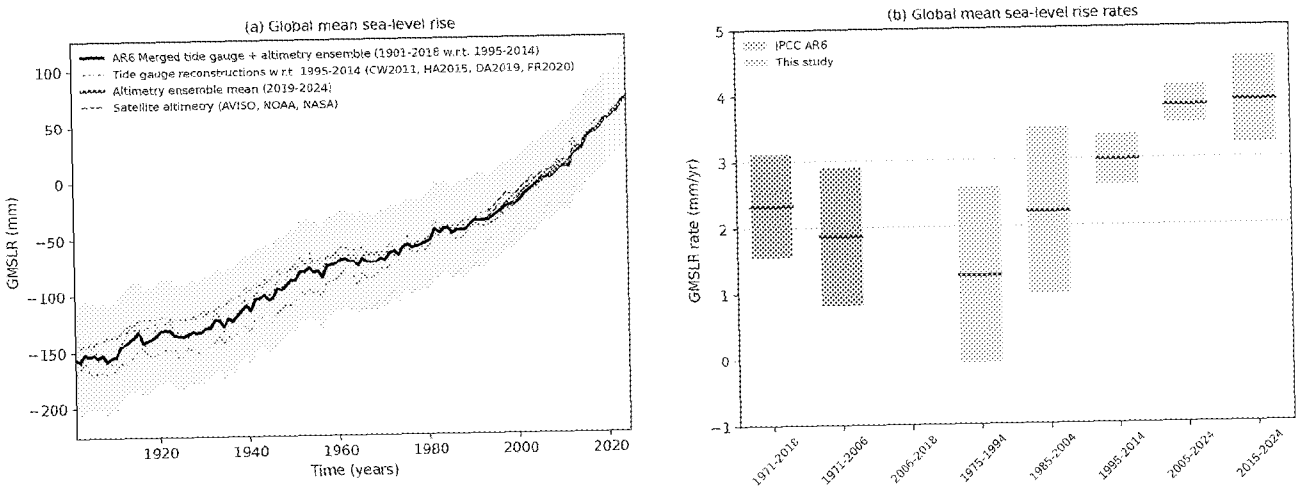

Figure 13. **(a)** Global mean sea-level rise time series 1901–2024 (mm). The GMSLR ensemble from AR6 is in black, with respect to the period 1995–2014, and the updated satellite altimetry ensemble is in red, with respect to the AR6 ensemble in 2018. Individual time series are shown by dashed lines. **(b)** GMSLR rates (mm yr^{-1}) for different periods. Uncertainties in **(a)** show the likely range and in **(b)** the very likely range, computed relative to 1901, including estimates of both structural uncertainty and parametric uncertainty (Palmer et al., 2021).

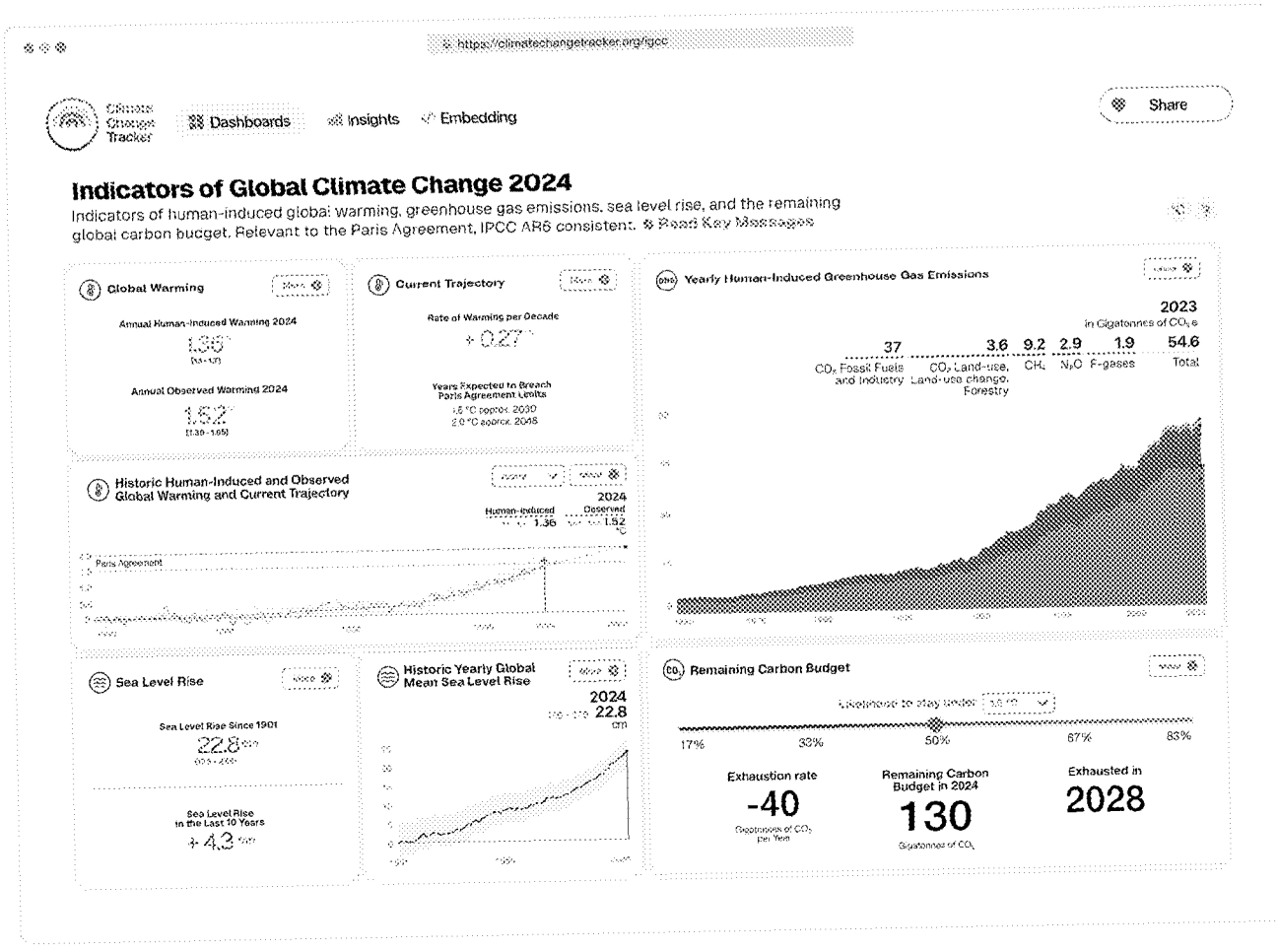

Figure 14. Screenshot of the IGCC dashboard (https://climatechangetracker.org/, last access: 13 June 2025, Climate Change Tracker, 2025).

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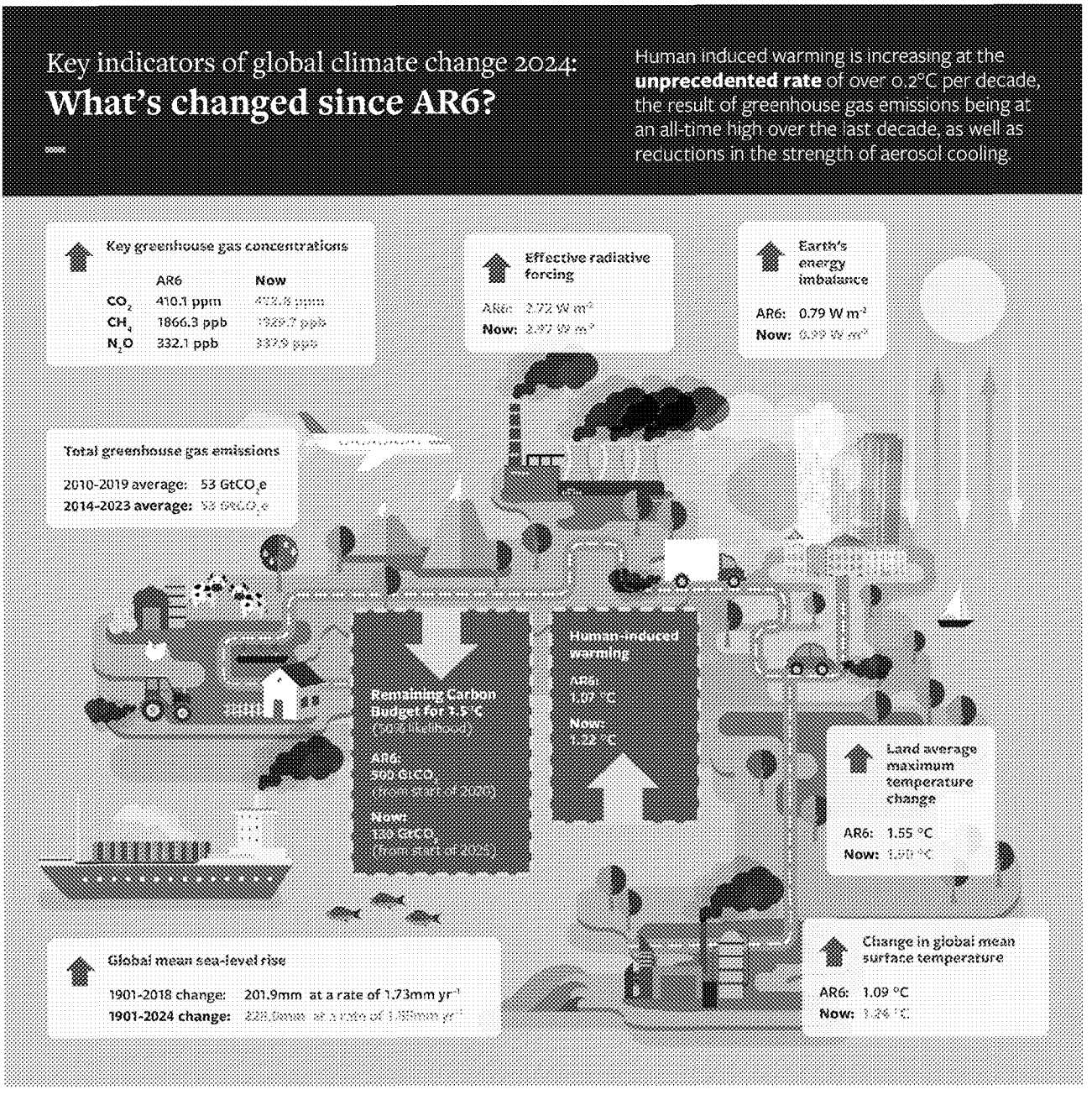

Figure 15. Infographic for the best estimate of headline indicators assessed in this paper.

14 Discussion and conclusions

The third year of the Indicators of Global Climate Change (IGCC) initiative has built on previous years' efforts to provide a comprehensive update of the climate change indicators required to estimate the human-induced warming and the remaining carbon budget. Table 11 and Fig. 15 present a summary of the headline indicators from each section compared to those given in the AR6 assessment. Table 11 also summarises methodological updates.

Last year (2024) witnessed global surface temperatures more likely than not exceeding 1.5 °C above pre-industrial levels which has widely been reported in the press. Sections 7 and 8 show that such high levels of global temperature anomalies are typical of what we expect from current best estimates of human-induced warming, modulated by internal climate variability.

The overview of key indicators of the state of global climate indeed highlights the multiple fingerprints of the 2023–2024 El Niño event regarding peak global surface tempera-

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ture (Sect. 7.2), regional dry anomalies in land precipitation (Sect. 11), and their implications for reduced land carbon sinks and the record growth rate of atmospheric CO_2 concentrations in 2024 (Sect. 3).

The overall increase in land maximum temperatures (Sect. 10), closely related to global warming levels, drives increasing trends in potential evapotranspiration, decreasing trends in soil moisture (Seo et al., 2025), contributing to the increased rate of global mean sea-level rise (Sect. 12).

Methane and biomass emissions had a strong component of change related to climate feedbacks (Sects. 2 and 3). Such changes will become increasingly important over this century, even if the direct human influence declines. This year, we explored different inventory choices in Sect. 2. In future years a more consistent approach to attribution of atmospheric emissions, concentration change and radiative forcing should be developed, so it can be assessed in AR7.

It is hoped that this update can support the science community in its collection and provision of reliable and timely global climate data. In future years we are particularly interested in improving SLCF updating methods to get a more accurate estimate of short-term ERF changes. The work also highlights the importance of high-quality metadata to document changes in methodological approaches over time. This year we have extended the datasets with land precipitation and global mean sea-level rise. In future years we hope to improve the robustness of the indicators presented here and could update other AR6 assessments. Parallel efforts could explore how we might update indicators of regional climate extremes and their attribution, which are particularly relevant for supporting actions on adaptation and loss and damage.

Generally, scientists and scientific organisations have an important role as "watchdogs" to critically inform evidence-based decision-making. This annual update traced to IPCC methods can provide a reliable, timely source of trustworthy information; IGCC and the complementary updates of the State of the Climate (BAMS) and State of the Global Climate (WMO) reports very much rely on the continued support of high-quality global monitoring networks of atmospheric and climate data and also on open data sources that are regularly updated and easily accessed.

This is a critical decade: human-induced global warming rates are at their highest historical level, and 1.5 °C global warming might be expected to be reached or exceeded in around 5 years in the absence of cooling from major volcanic eruptions (Sects. 8 and 9). Yet this is also the decade when global GHG emissions could be expected to peak and begin to substantially decline. The indicators of global climate change presented here show that the Earth's energy imbalance has increased to around 1.0 W m^{-2}, averaged over the last 12 years (Sect. 5), which represents a 25 % increase on the value assessed for 2006–2018 by AR6. This also has implications for the committed response of slow components in the climate system (glaciers, deep ocean, ice sheets) and committed long-term sea-level rise (through ocean thermal expansion and land-based ice melt/loss), to be addressed further in future updates. However, rapid and stringent GHG emission decreases such as those committed to at COP28 could halve warming rates over the next 20 years (McKenna et al., 2021). Table 1 shows that global GHG emissions are at a long-term high, yet there are signs that their rate of increase has slowed. Depending on the societal choices made in this critical decade, a continued series of these annual updates could track an improving trend for some of the indicators herein discussed.

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Competing interests. The contact author has declared that none of the authors has any competing interests.

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DOJ_00000816

From: Steven Koonin <steven.koonin@gmail.com>
Sent: Saturday, July 5, 2025 11:32 AM
To: 'Judith Curry'; 'Roy W. Spencer'; 'John Christy'; 'Ross McKitrick'
Cc: 'Travis Fisher'; 'Josh Loucks'; 'Cohen, Seth'
Subject: Executive summary rewrite
Attachments: Executive summaryJuly5.docx

My rewrite of the Executive Summary attached.

Steve Koonin

DOJ_00000817

EXECUTIVE SUMMARY

This report critically evaluates the Fifth National Climate Assessment (NCA5), finding it an inadequate basis for climate and energy policies. The foundational chapters on climate science are shown to be deficient when judged by both statutory requirements and commonly accepted standards for scientific input to policymaking.

NCA5 falls short on issues of scientific integrity. Its advocacy tone, particularly in the Overview chapter, is inappropriate for a scientific report. The Assessment repeatedly conflates natural and anthropogenic climate changes. And there is an endemic overconfidence in its conclusions, including inflated certainty levels and exaggeration of the findings of its underlying sources.

NCA5 employs flawed methodologies. There is no consistency in the time periods it uses for trend analyses; short periods, prone to spurious results, are common. There is an overemphasis on implausibly extreme scenarios for future emissions and sea level rise. And the traceable accounts alleged to support key conclusions are inadequate, thereby undermining reproducibility and verification.

NCA5 suffers from a deficient review process. A review by the National Academy of Sciences, Engineering, and Medicine (NASEM) failed to challenge some fundamental flaws. And the NCA5 authors were free to ignore important criticisms from both NASEM and independent reviewers.

These points and others, detailed in the report, show NCA5's opening chapters to be a biased and incomplete portrayal of climate science that skews toward excessive climate risk. As this portrayal underpins its subsequent chapters dealing with the impacts of climate change, NCA5 should not be used as basis for climate and energy policies.

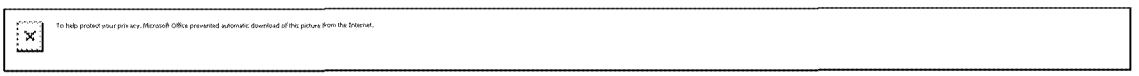
An NCA6 fit for policymaking would have a narrower scope than NCA5, refocusing on climate science including natural climate variability. It would be authored by a team that reflects the full diversity of scientific viewpoints and would be transparent, complete, and unbiased in its assessments.

From: Ross McKitrick <ross.mckitrick@gmail.com>
Sent: Sunday, August 3, 2025 4:18 PM
To: Roy W. Spencer; John Christy; Steven Koonin; Judith Curry; Josh Loucks; Travis Fisher
Subject: Fwd: Department Of Energy Report On The Impacts Of Greenhouse Gas Emissions

Francis Menton, aka the Manhattan Contrarian, is a lawyer who has been involved for years in climate litigation. He has a very supportive take on the report.

---------- Forwarded message ---------
From: **Manhattan Contrarian** <fmenton@manhattancontrarian.com>
Date: Sun, Aug 3, 2025 at 10:04 AM
Subject: Department Of Energy Report On The Impacts Of Greenhouse Gas Emissions
To: <ross.mckitrick@gmail.com>

View this email in your browser



Manhattan Contrarian

Excerpts:

Department Of Energy Report On The Impacts Of Greenhouse Gas Emissions

* On July 29 — the same day that EPA initiated the process of revoking the absurd "endangerment finding" that demonizes CO2 emissions from energy production (covered at Manhattan Contrarian here) — there was another equally momentous development on the energy front at the federal government. * On that day, the Department of Energy released a lengthy Report with the title "A Critical Review of Impacts of Greenhouse Gas Emissions on the U.S. Climate." (Although the Report bears a date of July 23, the 29th appears to be the date when it was signed by Energy Secretary Chris Wright and officially released.) * The Report is attributed to something called the "Climate Working Group," consisting of five prominent members of the climate skeptic community: John Christy, Judith Curry, Steven Koonin, Ross McKitrick, and Roy Spencer.
Read on »

More from the Manhattan Contrarian

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New York, NY 10004

Want to change how you receive these emails?

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From: John Christy [climateman60@gmail.com]
Sent: 7/18/2025 10:33:07 PM
To: Roy Spencer [roywspencer@hotmail.com]
CC: Judith Curry [curry.judith@gmail.com]; Ross McKitrick [ross.mckitrick@gmail.com]; Steven Koonin [steven.koonin@gmail.com]; Travis Fisher [travis.scott.fisher@gmail.com]; Josh Loucks [loucksj14@gmail.com]; Seth Cohen [seth.cohen@hq.doe.gov]
Subject: Re: NCA5 progress
Attachments: image001.jpg

That was done about a week ago.

John C.

On Fri, Jul 18, 2025 at 1:39 PM Roy Spencer <roywspencer@hotmail.com> wrote:
Did anyone notice NCA5 appears to have been scrubbed from agency websites? It's still on WayBack Machine. -Roy

Sent from my Verizon, Samsung Galaxy smartphone

-------- Original message --------
From: John Christy <climateman60@gmail.com>
Date: 7/18/25 1:31 PM (GMT-06:00)
To: Judith Curry <curry.judith@gmail.com>
Cc: Ross McKitrick <ross.mckitrick@gmail.com>, Roy Spencer <roywspencer@hotmail.com>, Steven Koonin <steven.koonin@gmail.com>, Travis Fisher <travis.scott.fisher@gmail.com>, Josh Loucks <loucksj14@gmail.com>, Seth Cohen <seth.cohen@hq.doe.gov>
Subject: Re: NCA5 progress

All

Attached are my edits in green highlight. I added a recommendation for NCA6 and attached here is a short writeup that motivates the recommendation.

John C.

On Fri, Jul 18, 2025 at 11:26 AM Judith Curry <curry.judith@gmail.com> wrote:
I suspect FEMA isn't one of USGCRP agencies. Also probably not USACE. IMO, NCA should be targeted at those orgs

On Fri, Jul 18, 2025 at 8:31 AM Ross McKitrick <ross.mckitrick@gmail.com> wrote:
That's excellent. I'd be interested in someone at FEMA providing feedback on our NCA report.

On Fri, Jul 18, 2025 at 9:50 AM John Christy <climateman60@gmail.com> wrote:
A couple of my folks did a quick write up of the TX floods.

https://www.earthdata.nasa.gov/dashboard/stories/tx-flood

John C.

On Fri, Jul 18, 2025 at 9:22 AM Judith Curry <curry.judith@gmail.com> wrote:
Thoughts on turning section 8.4 into a separate chapter, e.g.

8. Regional example: Texas 2025 floods

9. Conclusions and recommendations for NCA6

On Fri, Jul 18, 2025 at 3:28 AM Roy Spencer <roywspencer@hotmail.com> wrote:
I've added several edits to Judy's version (attached).

-Roy

From: Steven Koonin <steven.koonin@gmail.com>
Sent: Wednesday, July 16, 2025 5:29 AM
To: 'Judith Curry' <curry.judith@gmail.com>; 'Ross McKitrick' <ross.mckitrick@gmail.com>
Cc: 'John Christy' <climateman60@gmail.com>; 'Travis Fisher' <travis.scott.fisher@gmail.com>; 'Roy W. Spencer' <roywspencer@hotmail.com>; 'Josh Loucks' <loucksj14@gmail.com>; 'Seth Cohen' <seth.cohen@hq.doe.gov>
Subject: RE: NCA5 progress

And my further edits attached.

Do keep me at least cc'd over the next few days – I'll respond as I'm able.

SEK

From: Judith Curry <curry.judith@gmail.com>
Sent: Tuesday, July 15, 2025 7:05 PM
To: Ross McKitrick <ross.mckitrick@gmail.com>
Cc: John Christy <climateman60@gmail.com>; Steven Koonin <steven.koonin@gmail.com>; Travis Fisher <travis.scott.fisher@gmail.com>; Roy W. Spencer <roywspencer@hotmail.com>; Josh Loucks <loucksj14@gmail.com>; Seth Cohen <seth.cohen@hq.doe.gov>
Subject: Re: NCA5 progress

Here is my revised version. One proposed change of substance, relates to TX floods.

In section 8.3, i proposed modifying one of the bullets:

- The range of climatic and weather conditions, including extremes, that have occurred in the past and can reasonably be expected to occur in U.S. regions over the near future. An example of a salient acute failure is

the NCA5 chapter (region that includesTexas) that fails to mention the historical occurrence and future risk of flash floods in the Texas Hill Country ROSS MAYBE MENTION WHAT NCA5 SAID ABOUT TX FLOODS in REGIONAL CHAPTER, THEN INCLUDE LINK TO YOUR MINI ANALYSIS

An alternative approach would be to add a new chapter on Failure to document the risk of extreme events based on the historical data base, something like that. Simpler just to mention it in Section 8.3

On Tue, Jul 15, 2025 at 3:33 PM Ross McKitrick <ross.mckitrick@gmail.com> wrote:

> If Steve's away until Tuesday a Friday July 18 deadline won't be feasible, so let's work towards a Friday July 25 deadline.
>
> I propose this week we go in the following order to prevent us working on overlapping drafts
>
> Judy goes through the draft tonight
>
> Steve has another look tomorrow.
>
> Then Roy, then John, then me.

On Tue, Jul 15, 2025 at 3:47 PM John Christy <climateman60@gmail.com> wrote:

> I like Judy's idea. It's one way to avoid going through the preparation and experience of something like a colonoscopy twice in one month.
>
> John C.

On Tue, Jul 15, 2025 at 2:12 PM Judith Curry <curry.judith@gmail.com> wrote:

> Here is a way around the NCA4 issue, propose adding the following text to end of section 8.3
>
> NCA4 provided a better assessment than NCA5 in terms of a more thorough consideration climate science, use of data back to 1901, and less of an advocacy tone. However, NCA4 shared the following endemic problems with NCA5
>
> - Overconfidence in conclusions
> - Inadequate treatment of natural variability
> - Inadequate Traceable Accounts and communication of uncertainty
> - Over reliance on extreme scenarios

On Tue, Jul 15, 2025 at 12:02 PM Steven Koonin <steven.koonin@gmail.com> wrote:

> Just a heads up that I will be on the West Coast with very limited connectivity from tomorrow (Wednesday) evening through Monday evening (West Coast times). Back on the East Coast early Tuesday morning.
>
> SEK

From: Travis Fisher <travis.scott.fisher@gmail.com>
Sent: Tuesday, July 15, 2025 1:47 PM
To: Steven Koonin <steven.koonin@gmail.com>
Cc: Judith Curry <curry.judith@gmail.com>; Ross McKitrick <ross.mckitrick@gmail.com>; John Christy <climateman60@gmail.com>; Roy W. Spencer <roywspencer@hotmail.com>; Josh Loucks <loucksj14@gmail.com>; Seth Cohen <seth.cohen@hq.doe.gov>
Subject: Re: NCA5 progress

Hi all,

If we need to move quickly to publish the NCA critique as a DOE product, what would be a reasonable date for us to consider it final from the authors' point of view (subject to internal review for errors but not subject to political meddling)? I have to build a publication schedule, and I'd like to work backward from a date that's comfortable for you all.

I ask because the political powers that be are interested in having a published version to cite. Sooner is better, of course, but I don't want to jam you up. They certainly want it to be published before we could conceivably have a new head of the USGCRP, so it will have to be a DOE report.

Finally, if you're considering critiquing the entire NCA apparatus and previous reports, I think that would be helpful. The political response to an NCA5 critique so far has been (I'm paraphrasing), "Even if we show that NCA5 is not a solid basis for policymaking, what about NCA4 and prior reports?"

As always, please feel free to call me or convene a meeting if you want to discuss anything. I'll also try to keep everyone posted as the CWG report moves through the necessary hoops.

Best,

Travis

On Tue, Jul 15, 2025 at 11:41 AM Steven Koonin <steven.koonin@gmail.com> wrote:

I've marked up Judy's "desnarked" version (attached). Mostly typos and wording, but a few issues of substance. And still on the fence about whether and how to include the NCA4 story on temperature extremes.

SEK

From: Judith Curry <curry.judith@gmail.com>

Sent: Sunday, July 13, 2025 3:12 PM
To: Ross McKitrick <ross.mckitrick@gmail.com>
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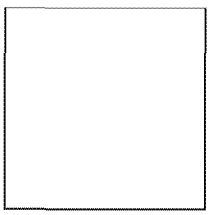

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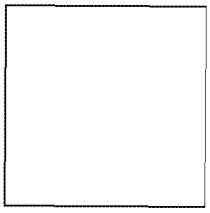

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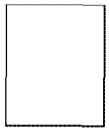

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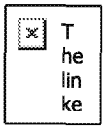

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Cc: Ross McKitrick; Steven Koonin; Travis Fisher; Josh Loucks; Seth Cohen
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Did anyone notice NCA5 appears to have been scrubbed from agency websites? It's still on WayBack Machine.
-Roy

Sent from my Verizon, Samsung Galaxy smartphone

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Date: 7/18/25 1:31 PM (GMT-06:00)
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Just a heads up that I will be on the West Coast with very limited connectivity from tomorrow (Wednesday) evening through Monday evening (West Coast times). Back on the East Coast early Tuesday morning.

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Hi all,

If we need to move quickly to publish the NCA critique as a DOE product, what would be a reasonable date for us to consider it final from the authors' point of view (subject to internal review for errors but not subject to political meddling)? I have to build a publication schedule, and I'd like to work backward from a date that's comfortable for you all.

I ask because the political powers that be are interested in having a published version to cite. Sooner is better, of course, but I don't want to jam you up. They certainly want it to be published before we could conceivably have a new head of the USGCRP, so it will have to be a DOE report.

Finally, if you're considering critiquing the entire NCA apparatus and previous reports, I think that would be helpful. The political response to an NCA5 critique so far has been (I'm paraphrasing), "Even if we show that NCA5 is not a solid basis for policymaking, what about NCA4 and prior reports?"

As always, please feel free to call me or convene a meeting if you want to discuss anything. I'll also try to keep everyone posted as the CWG report moves through the necessary hoops.

Best,

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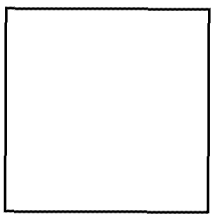

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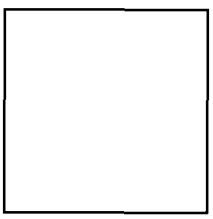

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- Inadequate Traceable Accounts and communication of uncertainty
- Over reliance on extreme scenarios

On Tue, Jul 15, 2025 at 12:02 PM Steven Koonin <steven.koonin@gmail.com> wrote:

Just a heads up that I will be on the West Coast with very limited connectivity from tomorrow (Wednesday) evening through Monday evening (West Coast times). Back on the East Coast early Tuesday morning.

SEK

From: Travis Fisher <travis.scott.fisher@gmail.com>
Sent: Tuesday, July 15, 2025 1:47 PM
To: Steven Koonin <steven.koonin@gmail.com>
Cc: Judith Curry <curry.judith@gmail.com>; Ross McKitrick <ross.mckitrick@gmail.com>; John Christy <climateman60@gmail.com>; Roy W. Spencer <roywspencer@hotmail.com>; Josh Loucks <loucksj14@gmail.com>; Seth Cohen <seth.cohen@hq.doe.gov>
Subject: Re: NCA5 progress

Hi all,

If we need to move quickly to publish the NCA critique as a DOE product, what would be a reasonable date for us to consider it final from the authors' point of view (subject to internal review for errors but not subject to political meddling)? I have to build a publication schedule, and I'd like to work backward from a date that's comfortable for you all.

I ask because the political powers that be are interested in having a published version to cite. Sooner is better, of course, but I don't want to jam you up. They certainly want it to be published before we could conceivably have a new head of the USGCRP, so it will have to be a DOE report.

Finally, if you're considering critiquing the entire NCA apparatus and previous reports, I think that would be helpful. The political response to an NCA5 critique so far has been (I'm paraphrasing), "Even if we show that NCA5 is not a solid basis for policymaking, what about NCA4 and prior reports?"

As always, please feel free to call me or convene a meeting if you want to discuss anything. I'll also try to keep everyone posted as the CWG report moves through the necessary hoops.

Best,

Travis

On Tue, Jul 15, 2025 at 11:41 AM Steven Koonin <steven.koonin@gmail.com> wrote:

I've marked up Judy's "desnarked" version (attached). Mostly typos and wording, but a few issues of substance. And still on the fence about whether and how to include the NCA4 story on temperature extremes.

SEK

From: Judith Curry <curry.judith@gmail.com>

Sent: Sunday, July 13, 2025 3:12 PM
To: Ross McKitrick <ross.mckitrick@gmail.com>
Cc: Steven Koonin <steven.koonin@gmail.com>; John Christy <climateman60@gmail.com>; Roy W. Spencer <roywspencer@hotmail.com>; Travis Fisher <travis.scott.fisher@gmail.com>; Josh Loucks <loucksj14@gmail.com>; Seth Cohen <seth.cohen@hq.doe.gov>
Subject: Re: NCA5 progress

see attached for a shorter, desnarked version of NCA5 for you to consider. I didn't do track changes, its clean text

On Sun, Jul 13, 2025 at 10:55 AM Ross McKitrick <ross.mckitrick@gmail.com> wrote:

Steve- this is the most recent version I have. There is also a Supplement on precip trends.

On Sat, Jul 12, 2025 at 6:18 PM Steven Koonin <steven.koonin@gmail.com> wrote:

Ross- Can you send around the most recent version of the NCA5 review. I can't seem to identify it in the emails and would like to go through it again in the next few days.

SEK

From: Ross McKitrick <ross.mckitrick@gmail.com>
Sent: Friday, July 11, 2025 3:49 PM
To: John Christy <climateman60@gmail.com>
Cc: judith curry <curry.judith@gmail.com>; Roy W. Spencer <roywspencer@hotmail.com>; Steven Koonin

<steven.koonin@gmail.com>; Travis Fisher <travis.scott.fisher@gmail.com>; Josh Loucks <loucksj14@gmail.com>; Seth Cohen <seth.cohen@hq.doe.gov>
Subject: Re: NCA5 progress

John and I only appear in Section 4.1 as part of challenging the reproducibility of the NCA5 Key Message regarding precipitation. 2 of our 3 citations in the reference list are data archives which are there for transparency purposes.

On Fri, Jul 11, 2025 at 2:53 PM John Christy <climateman60@gmail.com> wrote:

Judy

I must be missing something. Our papers directly address the issues espoused by NCA5. We offer all the data and methods. Why should our work be suppressed?

John C.

Sent from my iPhone

On Jul 11, 2025, at 1:16 PM, judith curry <curry.judith@gmail.com> wrote:

We need to think about our audience who we want to reach and influence. We don't want this to be another salvo in the climate wars. But to rise above it and be hyper objective.

Sent from my iPhone

On Jul 11, 2025, at 10:07 AM, John Christy <climateman60@gmail.com> wrote:

Judy

... Christy, McKitrick and Koonin ... you could look at it this way: we're the only ones willing to stick our heads up when the bullets are flying and endure protracted battles with editors and reviewers. Publishing in journals in this "climate" takes its toll, and most folks with an objective side just give up. We would love to cite other authors who do these NCA5-type analyses using the proper methods ... there just aren't many out there. As you know, there's no profit (or funding) in fighting the climate establishment. However, please, let us know if you see something we've missed.

John C.

On Fri, Jul 11, 2025 at 11:21 AM Judith Curry <curry.judith@gmail.com> wrote:

Re 1.4 and TX, i suggest we incorporate these points briefly in existing chapters. The content of 1.4 is already covered in CWG, apart from the convoluted peer review issue. CWG adequately covers temperature extremes, we don't need more of that in NCA beyond length of temperature records. Re TX, might fit best in CWG attribution, but its too early for that I think.

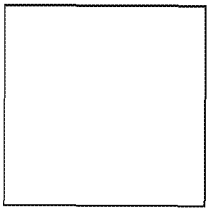
In 8.3 Recommendations for NCA5, we should recommend an increased focus on predicting individual extreme events and communicating the forecast, rather than attributing them to whatever.

What i'm struggling with in the NCA5 critique is that if you read it without an author list, you would figure the authors are christy, mckitrick, koonin. This should be a relatively short, high-level critique and IMO we need to depersonalize this

On Fri, Jul 11, 2025 at 8:19 AM Ross McKitrick <ross.mckitrick@gmail.com> wrote:

> We seem to have stalled on iterating the NCA5 report. Here are the issues on the table:
>
> 1. Whether to drop Section 1.4
>
> - my thinking is I like the idea of the section because it justifies why we would presume to critique a report that has already gone through 11 government agencies and a National Academies review. At the same time I think it could be shortened and made more effective with a different version of the Figure from CWG25. John if you can you send me the spreadsheet you used I'll propose a rewrite.
>
> 2. Do we include a case study of the Texas floods?
>
> - What I like about that section is that it is a vivid example of how a document that could have provided useful info for disaster planners not only failed to do so, but it would have misdirected resources if they were to have relied on it. But it's easy to have 20/20 hindsight. Presumably somewhere in the US at this moment there are several potential weather-related hazards poised to cause death and destruction later this year, and the local authorities are not ready for them. We need to explain what it would look like for an NCA to be a useful resource in that context. What say ye all?
>
> 3. Tidying
>
> - I find the LLM critiques to be somewhat helpful in anticipating possible lines of attack, but they are overly algorithmic and often end up saying "they make a valid point but that's not the consensus so it's probably wrong." And it seems to have hallucinated about things we didn't even say. Still, it points to the need to guard against snark.

--



Judith Curry, President
CFAN - Climate Forecast Applications Network
Reno, NV USA
curry.judith@cfanclimate.com |
+1.404.803.2012
http://www.cfanclimate.net

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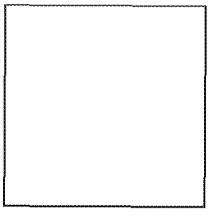

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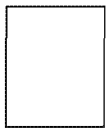

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CFAN - Climate Forecast Applications Network
Reno, NV USA
curry.judith@cfanclimate.com |
+1.404.803.2012
http://www.cfanclimate.net

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http://www.cfanclimate.net

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Judith Curry, President
CFAN - Climate Forecast Applications Network
Reno, NV USA
curry.judith@cfanclimate.com |
+1.404.803.2012

Critique of the Fifth National Climate Assessment

EXECUTIVE SUMMARY 3

1 INTRODUCTION 4

1.1 About this Report 4
1.2 About the National Climate Assessments 4
1.3 Standards for Assessing NCA Products 5

2 NCA5 OVERVIEW CHAPTER: ADVOCACY LANGUAGE AND UNSCIENTIFIC TONE 6

3 OVERCONFIDENCE WHEN STATING CONCLUSIONS 7

3.1 Inflated certainty levels 7
3.2 Overstating findings in underlying sources 9
3.3 Example: Emergent constraints 9

4 ARBITRARY AND AMBIGUOUS TREND ANALYSES 10

4.1 Average and Extreme Precipitation 11
4.2 Heatwaves 11

5 INADEQUATE TRACEABLE ACCOUNTS 14

6 OVEREMPHASIS ON EXTREME SCENARIOS 16

7 CONFLATION OF NATURAL AND ANTHROPOGENIC CLIMATE CHANGES 18

8 SUMMARY EVALUATION OF NCA5 AND RECOMMENDATIONS FOR NCA6 19

8.1 Compliance with USGCRP's statutory obligation 19
8.2 Adherence to the tenets of Gold Standard Science 20
8.3 Suitability for informing Federal climate and energy policy 20
8.4 NCA5 and the 2025 Texas Floods 22
8.5 Recommendations for NCA6 24

9 REFERENCES 25

10 APPENDIX: CHARGE TO THE REVIEW 27

ABOUT THE AUTHORS 28

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EXECUTIVE SUMMARY

This report critically evaluates the Fifth National Climate Assessment (NCA5), finding it an inadequate basis for climate and energy policies. A detailed review of the foundational chapters on climate science raises several key concerns:

Scientific Integrity

- An advocacy tone, particularly in the Overview chapter, that is inconsistent with scientific objectivity
- Endemic overconfidence when stating conclusions, including inflated certainty levels and overstatement of findings from underlying sources
- No mentions of dissent, disagreement or controversies
- Policy prescriptions that ignore costs and tradeoffs

Flawed methodology

- Minimal discussion of observational inadequacies
- Use of short time periods for trend analyses; lack of a consistent rationale for choosing time scales
- Attribution is implied, not dissected
- Overemphasis on extreme scenarios for future emissions and sea level rise
- Inadequate traceable accounts to support key conclusions

Inadequate Review Process

- A review by the National Academy of Sciences, Engineering, and Medicine (NASEM) failed to identify some fundamental flaws in NCA5
- The NCA5 authors failed to adopt some improvements recommended by NASEM

The report shows NCA5 to be a biased and incomplete picture of climate science that skews toward excessive climate risk. Consequently, NCA5 should not be used as a basis for climate and energy policies.

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1 INTRODUCTION

1.1 About this Report

This report responds to a request from the Office of Science and Technology Policy (OSTP) Director Michael Kratsios (reproduced in the Appendix) [MAY HAVE TO MODIFY THIS] that we assess the suitability of the Fifth National Climate Assessment (NCA5 2023) for informing climate and energy policies.

To conduct this assessment, we reviewed NCA5 itself, the National Academies of Science, Engineering and Medicine (NASEM) review of the Third Order NCA5 Draft, and the USGCRP responses to that review. We have drawn upon our long experience working on advisory reports, including for the NASEM, the Intergovernmental Panel on Climate Change (IPCC), and other organizations as writers, reviewers, and study leaders. We have reviewed recent scientific developments in a separate report to Energy Secretary Wright (Climate Working Group 2025) herein denoted "CWG25".

We find that NCA5 should not be relied on for policy making as it portrays an incomplete and misleading picture of current climate variability and how climate-related risks are or are not changing over time. NCA5 was selective and incomplete in its survey of climate science. The overall effect of its biases and omissions is an unfocused and excessively dire picture of climate risk.

To support our finding, the following sections of this chapter provide some background on the National Climate Assessments and the standards by which we have assessed NCA5. Chapters 2 through 7 detail important ways in which NCA5 fails to meet those standards. Finally, Chapter 8 summarizes our evaluation of NCA5 and makes recommendations for NCA6.

1.2 About the National Climate Assessments

The U.S. Global Change Research Program (USGCRP) was established by Presidential Initiative in 1989 and mandated by Congress in the Global Change Research Act (GCRA) of 1990 to develop and coordinate "a comprehensive and integrated United States research program which will assist the Nation and the world to understand, assess, predict, and respond to human-induced and natural processes of global change."

The National Climate Assessment (NCA) Reports evolved from the GCRA requirement to:

> Prepare and submit to the President and the Congress an assessment which (1) integrates, evaluates, and interprets the findings of the Program and discusses the scientific uncertainties associated with such findings; (2) analyzes the effects of global change on the natural environment, agriculture, energy production and use, land and water resources, transportation, human health and welfare, human social systems, and biological diversity; and (3) analyzes current trends in global change, both human-induced and natural, and projects major trends for the subsequent 25 to 100 years.

The five NCA Reports to date have interpreted this mandate in different ways:

- NCA1 (2000) was a multidisciplinary effort to study and portray in regional detail the potential effects of human-induced global warming on the United States.

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- NCA2 (2009) was a relatively short report that not only focused on the potential consequences of climate change but also sought to identify potential adaptation measures and identify the highest priorities for future research.
- NCA3 (2014) was an expanded effort that continued along the lines of NCA2, and was distinguished by a comprehensive review process, including a review by the National Academy of Sciences. NCA3 introduced a traceability analysis for each key finding, including a description of uncertainties.
- NCA4 (2017/2018) was a further expanded effort that was published in two volumes: I Climate Science Special Report (CSSR), and II Impacts, Risk, and Adaptation in the United States. This was the first NCA report to devote significant effort to assessing climate science.
- NCA5 (2023) returned to a single volume format, reducing discussion of climate science to a cursory two chapters, with continuing focus on regional and sectoral impacts of climate change. NCA5 expanded its remit to topics that are arguably outside the purview of the USGCRP, focusing on "Climate Action" and policy recommendations with a social justice emphasis.

These successive interpretations of the NCA are poorly aligned with the GCRA's statutory requirements. Only NCA4 gives serious consideration to climate science, which receives the great majority of USGCRP funding, and even then NCA4 misrepresents some important points. Natural climate variability is essentially dismissed as unimportant in NCA4 and barely mentioned in NCA5 in most contexts, despite the mandate to include both human-caused and natural climate change. Most significantly, NCA5 has redirected the focus away from climate science and even the hazard elements of impacts, towards evaluation of societal vulnerabilities and advocacy for particular policy options, especially deployment of wind and solar power generation.

1.3 Standards for Assessing NCA Products

Beyond the statutory requirements stated above, another pertinent standard is President Trump's executive order of May 23, 2025, Restoring Gold Standard Science. It enumerates some of the characteristics of good science, namely that it should be:

i. reproducible;
ii. transparent;
iii. communicative of error and uncertainty;
iv. collaborative and interdisciplinary;
v. skeptical of its findings and assumptions;
vi. structured for falsifiability of hypotheses;
vii. subject to unbiased peer review;
viii. accepting of negative results as positive outcomes; and
ix. without conflicts of interest.

For an assessment of policy relevant science, it is also important to include statements about the strength of knowledge. The IPCC's approach to assessing strength of knowledge is based on judgment of the available evidence and agreement among experts. But there are more sophisticated knowledge characterizations for risk management. Here are the elements according to Aven (2017):

- The degree to which the assumptions made are reasonable/realistic based on background knowledge

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- The degree to which data/information exists and are reliable and relevant
- The degree to which there is disagreement among experts (including those from different environments or academic fields)
- The degree to which the phenomena involved are understood and accurate models exist
- The degree to which the knowledge has been thoroughly examined with respect to unknown knowns (issues that are known to matter but are ignored, such as, in this context, natural variability).

2 NCA5 Overview Chapter: Advocacy language and unscientific tone

NCA5 Chapter 1, "Overview", holds a prominent place in the Report since it summarizes the entire report and is the only section that many will read. Chapter 1 is marred by an activist tone, language that aggressively promotes mitigation policies, and motivated optimism. As such, this chapter adds an imprimatur of scientific authority to naïve and simplistic declarations of opinion about public policy. Here are some examples.

Chapter 1 opens with:

> The more the planet warms, the greater the impacts. Without rapid and deep reductions in global greenhouse gas emissions from human activities, the risks of accelerating sea level rise, intensifying extreme weather, and other harmful climate impacts will continue to grow. Each additional increment of warming is expected to lead to more damage and greater economic losses compared to previous increments of warming, while the risk of catastrophic or unforeseen consequences also increases.

This statement presupposes that all warming is anthropogenic, that all warming is bad and causes economic damage, and that warming intensifies extreme weather. Such sweeping generalizations go well beyond what science has or can establish. The statement also refers to growing risks without reference to their magnitude – a small risk that increases might still be a small risk, and a large risk might be only incrementally worsened.

On the next page one finds:

> Each additional increment of warming leads to greater risks [here it lists 7 key components of society including food security and the economy] ... Without deeper cuts in global net emissions, climate risks to the US will continue to grow... Action to limit future warming and reduce risks can have near-term benefits and opportunities: low-carbon energy jobs, Improved air quality, Health benefits, Economic benefits..."

The authors write as if climate policy does not involve trade-offs and all measures to reduce future warming will be effective and beneficial. Neither the vast body of scholarship on climate science and economics nor historical experience support such simplistic claims (CWG25). Not every additional increment of warming leads to economic harms; in fact, NCA5 Chapter 19 acknowledges that there will also be benefits. Nor is climate policy guaranteed to benefit the economy; it could impose net costs. Such misleading statements are a disservice to policymakers.

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Pages 8 and 9 of the Overview promote renewable energy options by noting, correctly, that the levelized costs of wind/solar generation have fallen sharply since 2010, and so offers this rationale for pursuing deep emission reductions:

> Recent growth in the capacities of wind, solar, and battery storage technologies is supported by rapidly falling costs of zero- and low-carbon energy technologies, which can support even deeper emissions reductions. For example, wind and solar energy costs dropped 70% and 90%, respectively, over the last decade, while 80% of new generation capacity in 2020 came from renewable sources.

Yet it has long been known that intermittent renewables generation must be supplemented by dispatchable generation to meet grid reliability standards, and that doing so (*e.g.*, through natural gas, fission, or storage) significantly increases the total cost of electricity. Further, there are yet unmet synchronization challenges in electrical grids with heavy penetration of wind and solar generation. NCA5 fails to acknowledge these facts. But more importantly, we see no reason for NCA5 to be discussing renewable energy technologies and economics in the context of its mandate.

Page 17 of the Overview introduces the discussion of risks from extreme weather events by saying "Harmful impacts from more frequent and severe extremes are increasing across the country." This creates the impression that extreme weather events are worsening and that disaster losses are driven by trends in extreme weather. While the section goes on to acknowledge that some of the increase is due to increases in the exposure and value of assets at risk, it then invokes the NOAA Billion Dollar Dataset as evidence of extreme weather getting worse. Scientists have shown that this is an invalid metric (CWG25 Section 10.2) since it measures the growth of vulnerable infrastructure, not the frequency of extreme weather, and indeed NOAA has recently withdrawn the data product. Even though the dataset was still distributed by NOAA at the time of the NCA5, the report authors failed to assess it skeptically and see that it was unfit for the purpose of measuring climate trends.

Page 23 of the Overview states, in large font:

> Climate changes are making it harder to maintain safe homes and healthy families; reliable public services; a sustainable economy; thriving ecosystems, cultures, and traditions; and strong communities.

This statement cannot be evaluated on scholarly grounds and so doesn't belong in a scientific assessment report. Its prominent inclusion points not only to the willingness of NCA5 authors to promote alarm, but also the ineffectiveness of the review process in eliminating such statements.

3 OVERCONFIDENCE WHEN STATING CONCLUSIONS

3.1 Inflated certainty levels

Overconfidence in stating conclusions has been an endemic problem in NCA Reports. The authors frequently make sweeping generalizations without appropriate caveats or acknowledging uncertainties. The overconfidence begins with inflated language to describe certainty levels.

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NCA5 uses specific terms to convey information about scientific confidence associated with important findings, observations and projections. The Front Matter of NCA5 states that

> confidence in a finding is based on the type, amount, quality, strength, and consistency of evidence; the skill, range, and consistency of methods to detect, evaluate, attribute, and interpret climate trends; and the degree of agreement across scientific information sources.

Table 1 from the Front Matter provides calibrated language for confidence assessments:

Very high:	Strong evidence (established theory, multiple sources, well documented and accepted methods, etc.). High consensus
High:	Moderate evidence (several sources, some consistency, methods vary and/or documentation limited, etc.). Medium consensus
Medium:	Suggestive evidence (a few sources, limited consistency, methods emerging, etc.) Competing schools of thought.
Low:	Inconclusive evidence (limited sources, extrapolations, inconsistent findings, poor documentation and/or methods not tested, etc.). Disagreement or lack of opinions among experts.

This terminology is obviously inflated: *high confidence* with just moderate evidence and medium consensus; *medium confidence* with only suggestive evidence and competing schools of thought. This inflation in terminology leads to overconfidence in conclusions.

Even with this inflated terminology, NCA5 further inflates the confidence level of many of its conclusions to well beyond what the IPCC has concluded with more thorough justification, and by incorrectly applying its own standards. An example is the conclusion about anthropogenic influence on climate change, arguably one of the most important scientific statements of the report.

Key Message 3.1 Traceable Account states:

> There is *very high confidence* that emissions of GHGs from human activities, fossil fuel use in particular, have unequivocally caused *all* global warming observed over the industrial era.

while the corresponding statements from IPCC AR5 and AR6 are

> **AR5:** It is *extremely likely* that *more than half* of the observed increase in global average surface temperature from 1951 to 2010 was caused by the anthropogenic increase in greenhouse gas concentrations and other anthropogenic forcings together. (IPCC, 2013)

> **AR6:** The *likely* range of total human-caused global surface temperature increase from 1850–1900 to 2010–2019 is 0.8°C to 1.3°C, with a best estimate of 1.07°C. It is *likely* that well-mixed GHGs contributed a warming of 1.0°C to 2.0°C, other human drivers (principally aerosols) contributed a cooling of 0.0°C to 0.8°C, natural drivers changed global surface temperature by –0.1°C to +0.1°C, and internal variability changed it by –0.2°C to +0.2°C. It is *very likely* that well-mixed GHGs were the main driver of tropospheric warming since 1979.

The IPCC AR5 and AR6 statements provide likelihood assessments but not a confidence level. While NCA5 claims with *very high confidence* that fossil fuels have unequivocally caused *all* global warming, AR5 refers to "*more than half* of the observed warming" and AR6 provides a more nuanced statement that relates to a *likely* range of warming contributed to by human drivers.

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3.2 Overstating findings in underlying sources

Although we did not do a detailed audit of NCA5's use of source material, spot checks suggest a pattern of overstatement.

Chapter 2 page 11 reports on an increase in precipitation in some areas and attributes it to "climate change":

> Many eastern regions of the country are getting wetter (Figure 2.4). Average annual precipitation from 2002-2021 was 5%-15% higher relative to the 1901-1960 average in the central and eastern US, a trend attributable to climate change.

NCA5 attributes the claim to Knutson and Zeng (2018). But Knutson and Zeng did not say these things nor did they analyze this particular period. For 1981-2010 they cautioned that observed changes are consistent with natural variability, and they did not claim attributable trends were observed over the United States.

As another example of overstating findings, NCA5's Chapter 2 page 18 states

> There is robust evidence that human-caused warming has contributed to increases in the frequency and severity of the heaviest precipitation events across nearly 70% of the US.

This is apparently attributed to Diffenbaugh *et al.* (2018) and Kirchmeier-Young and Zhang (2020). Diffenbaugh *et al.* presented ratios of observed occurrences of extreme events to simulated occurrence rates in CMIP6 models run with only natural forcings. They report that for 79% of the U.S., extreme rainfall events are currently more frequent than in simulations, and the ratio of occurrences will rise under future warming simulations. This is not "robust" evidence of anthropogenic influence since it requires readers to assume that climate models accurately simulate regional precipitation patterns, something that the IPCC AR6 states is uncertain (AR6 WGI SPM Box SPM 1.2, SPM Section C.1.3).

Kirchmeier-Young and Zhang used three global climate models to analyze extreme 1- and 5-day events in North America. They noted large differences among the three models in their simulated precipitation changes. Attribution results for the U.S. are reported in their online Supplement (Figure S4). Across six experiments (three models and two rainfall metrics) anthropogenic influence was detected in only one case. Also both cited references began their historical observational records only in 1961. Here again this is not "robust" evidence. It is merely suggestive, particularly since other studies have found natural variability to be predominant.

3.3 Example: Emergent constraints

Some of the overconfidence expressed by NCA5 arises by omitting discussion of counterevidence in the peer reviewed literature, ignoring dissent and disagreement. An example is the topic of "emergent constraints". NCA5 Chapter 3 page 17 invokes this concept to support its claim that key uncertainties in climate model projections have been reduced:

> An approach to reduce uncertainty in climate change projections has matured over the past decade. It is known as "emergent constraints." The term refers to strong statistical

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> relationships between highly uncertain future climate parameters and observable trends or variations in the current climate, along with a physical explanation of this relationship.

Emergent constraints appeared in the climate modeling literature as an attempt to tie climate model behavior to climate observations in hopes of generating insight into real-world equilibrium climate sensitivity (ECS). Climate models exhibit a wide range of ECS values. The idea of emergent constraints is to examine whether the models with shared sensitivity values also share a common representation of some climate process (usually related to clouds) that might influence ECS. Suppose, for example, that in low-ECS models the total cloud fraction in the tropics is strongly correlated with that in the southern midlatitudes, but in high-ECS models the correlation is weak. Then researchers could examine whether the observed correlation is strong or weak and draw a conclusion about which type of model, and therefore which ECS value, is more likely.

A problem in the emergent constraint literature is that there has been a proliferation of proposed correlations with little physical basis. NCA5 alludes to this in the Traceable Accounts section (p. 3-40) but not in the main chapter text. As shown by Schlund *et al.* (2020), many emergent constraints patterned on CMIP5 models (Coupled Model Intercomparison Project Phase 5, used for the IPCC 5th Assessment Report) failed to work on CMIP6 models (used for the IPCC 6th Assessment Report). In other words, the correlations between ECS and cloud processes present in CMIP5 models were absent in CMIP6 models, indicating that they were likely spurious rather than clues to physical processes governing the climate system. As a result, emergent constraints estimated on CMIP5 models *increased* the uncertainty of ECS, rather than decreasing it as claimed by NCA5.

Yet NCA5 incorrectly described the use of emergent constraint analysis as an advance that reduced the uncertainty of ECS and climate model projections (p. 3-38):

> Emergent constraints have been widely applied to reduce the simulated spread in the climate feedbacks that shape climate sensitivity.

4 ARBITRARY AND AMBIGUOUS TREND ANALYSES

CWG25 Chapter 6 discussed the need for care in the choice of time scale when making claims about trends in extreme weather. We provided examples from analysis of river flooding, heatwaves, and extreme precipitation to show how assertions about apparent trends based on short data sets fall apart when considering longer versions of the same data sets. NCA5 uses varying time periods for trend analyses, especially in Chapter 2 (which is focused on trends), without explaining why shorter or longer intervals were chosen. For example, page 2-4 defines temperature trends over the interval since the late 1800s whereas page 3-29 presents temperature trends over 1972-2021. Page 2-11 compares rainfall over the 2002-21 versus 1901-1960 intervals, while page 2-18 uses the interval since the late 1950s to compute trends.

A further problem is that NCA5 uses the term "trend" repeatedly without indicating if it is statistically significant (*i.e.*, distinguishable from random variability); the ambiguity creates the impression all the observed changes were significant, but readers are left to speculate. All climate variables will drift up or down over any particular time interval. Identifying the change as a trend requires showing that it is statistically significant using a variance estimator suitable for the type of data being analysed. Of particular importance is choosing a method robust to the serial correlation that is frequently present in climate data. Throughout Chapters 1 to 3, references are made to "trends" without explaining how

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they were computed. The exception was on page 1-19 which refers to urban temperature trends being calculated using the Theil-Sen estimator, although that method does not seem to have been used elsewhere. The one case where reference is made to statistical significance is on Page 2-9, referring to a trend in Atmospheric Optical Depth, but there is no explanation of how significance was determined. Page 2-19 refers to regional trends in droughts being "robust" but again fails to explain how the term was defined.

4.1 Average and Extreme Precipitation

NCA5 did not continue the NCA4 precedent of using the post-1901 interval as the time scale for its precipitation discussion. Instead, it refers to changes "since the 1950s"; NCA5 Figure 2.8 suggests 1958 might be the intended start date. Under Key Message 2.2, "Extreme Events Are Becoming More Frequent and Severe", NCA5 states (p. 2-18):

> Rainfall is becoming more extreme
> Since the 1950s, there has been an upward trend in heavy precipitation across the contiguous US. This increase is driven largely by more frequent precipitation extremes, with relatively smaller changes in their intensity.

In addition to our concerns that inferences about trends are contingent on choice of time scale, if the intended meaning of this statement is that positive and significant trends are found in heavy precipitation events across CONUS, we cannot reproduce it. In CWG25 Section 6.4, in addition to referencing previous analyses in the climate literature we presented analyses of daily U.S. precipitation data for the Pacific Coast, Southeast and Northeast regions, in all cases finding both considerable regional heterogeneity and that trends in various measures of extreme precipitation detectable on one time scale are often not detected on longer or shorter time scales. Additional analysis of stations in the upper Midwest confirm this pattern.[1] Moreover the NCA5 statement was at odds with evidence in the peer-reviewed literature (discussed in CWG25 Section 6.4) to which authors of this report drew NCA5 authors' attention during the review process.

The following is a more accurate summary of what U.S. precipitation data show.

> There are regionally heterogenous changes in average and extreme precipitation. Positive trends in annual average rainfall and extreme events (defined either as the annual maximum or the number of exceedances of the 99th percentile value) are generally weak or non-existent when looking at samples exceeding 130 years in length. Significant trends can be found when beginning the sample in the 1950s although in most cases the trends weaken and become insignificant when looking at the post-1980 interval. This argues against attribution of changes in precipitation to anthropogenic warming, which becomes the strongest post-1980.

4.2 Heatwaves

In contrast to NCA5, NCA4 examined heat extremes across the entire 20th century, pointing out that peak heat wave activity was reached in the 1930s and has decreased since then, and that recent increases are confined to areas west of the Rockies. NCA4 stated:

[1] See details at https://www.nsstc.uah.edu/data/ushcn_jrc/SI.Precipt_trends_reproducing.pdf, which provides access to data and code.

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[The] warmest daily temperature of the year increased in some parts of the West over the past century, but there were decreases in almost all locations east of the Rocky Mountains. In fact, all eastern regions experienced a net decrease, most notably the Midwest (about 2.2°F [1.2°C]) and the Southeast (roughly 1.5°F [0.8°C]).

Since the mid-1960s, there has been only a very slight increase in the warmest daily temperature of the year (amidst large interannual variability). Heat waves (6-day periods with a maximum temperature above the 90th percentile for 1961–1990) increased in frequency until the mid-1930s, became considerably less common through the mid-1960s, and increased in frequency again thereafter. As with warm daily temperatures, heat wave magnitude reached a maximum in the 1930s.
(NCA4 pp. 190-191)

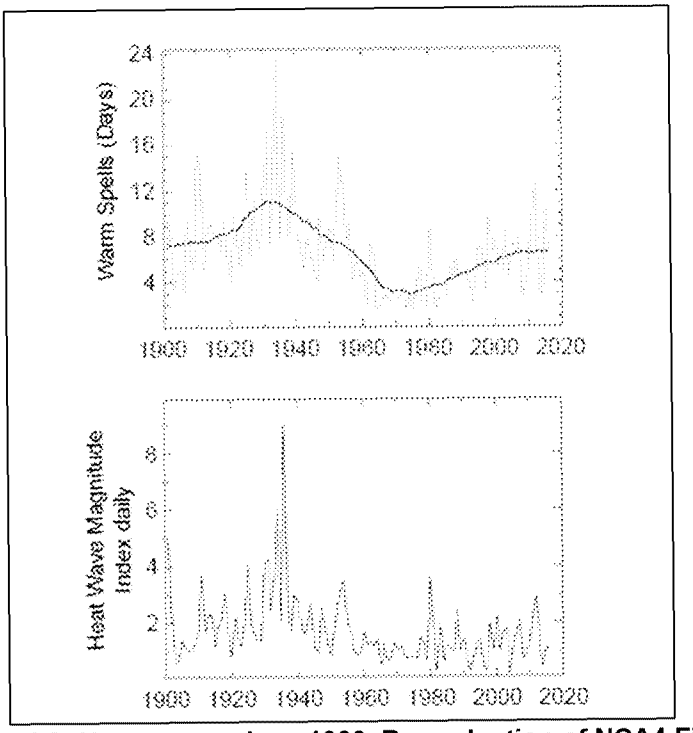

FIGURE 3. U.S. Heat waves since 1900. Reproduction of NCA4 Figure 6.4

Contrast this careful and factual language of with NCA4 with NCA5 Key Message 2.2: "Extreme Events Are Becoming More Frequent and Severe." This blanket statement is followed by NCA5 Figure 2.7 (reproduced as Figure 4 below) which shows the number of hot days, cold days and warm nights (respectively in panels a—c) over the period 2002-2021 compared to 1901-1960. Presumably these are annual counts, although this is not stated in the caption.

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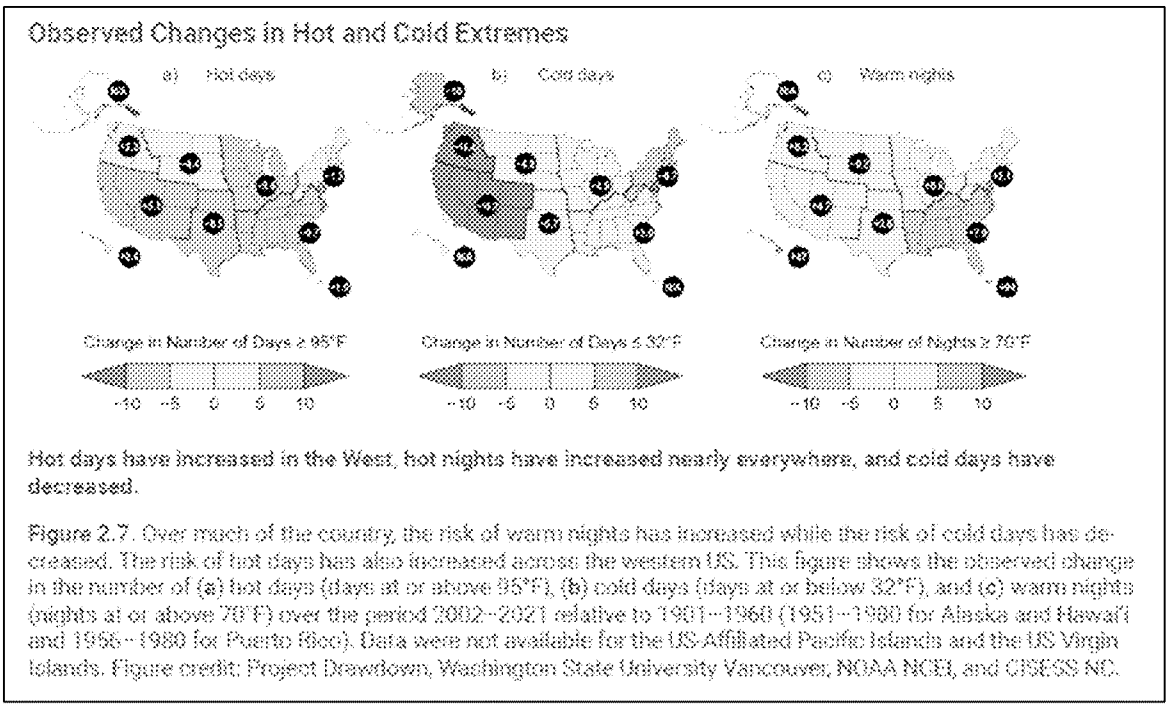

FIGURE 4: Reproduction of NCA5 Figure 2.7.

Close inspection shows that this figure actually contradicts the NCA5 Key Message with respect to heatwaves and instead reinforces the position of NCA4. Notwithstanding Key Message 2.2, the leftmost panel in NCA5 Figure 2.7 above shows that over most of CONUS the number of extreme heat days has *decreased* in recent decades compared to the prior century.

The accompanying discussion in NCA5 becomes convoluted as it appears to be aimed at supporting the Key Message despite the contrary evidence. NCA5 Chapter 2 elaborates on Key Message 2.2 by stating (page 2-16):

> Observations show an increase in the severity, extent, and/or frequency of multiple types of extreme events. Heatwaves have become more common and severe in the West since the 1980s (*high confidence*).

But while it mentions the increase in hot days in the West, it fails to mention the decrease everywhere east of the Rockies. On the next page (page 2-17) it raises the comparison to the 1930s and then switches to discussing global counts:

> By some measures, the most extreme heatwaves on record in the United States occurred during the Dust Bowl era of the 1930s. ... Globally such heatwaves are becoming more frequent, and in recent decades the western United States has been following those trends.

The reference to a global trend seems to be an attempt to tie heatwaves to anthropogenic climate change. But the obvious question, unaddressed by NCA5, is why one region follows the global pattern of increasing heatwaves while most of the country is trending in the opposite direction. These issues are addressed in Chapter 6 of CWG25, demonstrating that the range and magnitude of extreme temperatures are driven more by natural variability than by anthropogenic forcing. The analysis in CWG25 shows that for both (a) hot days (≥ 95°F) and (b) number of days in heatwaves, the current decade is no hotter than a century ago in the U.S. Thus, the NCA5 claim that "multiday heatwaves

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have become hotter, more frequent, larger, and longer lasting in recent decades," is simply false when expanding the temporal and spatial domains to encompass all available data (Chapter 6 and Figure 6.3.6 of CWG25).

NCA5 then pointed to the dramatic Pacific Northwest heatwave of 2021. CWG25 Section 8.6.1 discusses this event in detail, reviewing the multiple peer reviewed studies that explained the unusual meteorological context was unrelated to human-caused climate change, a point omitted from the NCA5 discussion.

NCA5 finally addresses the declining heatwave trend in CONUS east of the Rockies but attempts to reframe it by focusing on urban warm spells.

> [The] number of very hot days has actually decreased across the central and eastern regions due to summer cooling trends in the region (Figure 2.7; Ch. 22). This does not, however, mean the central and eastern US are not affected by heat. The impacts of extreme high temperatures are more severe if such conditions persist for several days, and overall, multiday heatwaves have become hotter, more frequent, larger, and longer lasting in recent decades. Across 50 large US cities, the US Global Change Research Program heatwave indicator (https://www.globalchange.gov/indicators/heat-waves) shows that the average number of heatwaves has doubled since the 1980s, and the length of the heatwave season has increased from about 40 days to about 70 days.

We discussed this part of NCA5 in CWG25 Section 6.3. The figure referenced by NCA5 uses a short time period which begins in the 1960s, the coldest decade in the last 100 years, thus suppressing any comparison to the 1930s. Further, nighttime temperatures in urban areas have increased faster than daytime temperatures (which NCA5 acknowledges), but this is a signature of urban heat islands and is not a good metric of climate change. CWG25 found that the occurrence of hot days (≥ 95° F) has recently increased in the West but declined since 1899 in the remainder of the country and in the nationwide average.

5 INADEQUATE TRACEABLE ACCOUNTS

NCA3 began the practice of including a section on Traceable Accounts at the end of each chapter. This is the description from NCA5:

> Each chapter concludes with a section entitled Traceable Accounts, which provides information on the overall process used to develop the chapter as well as a separate Traceable Account section for each Key Message. These Traceable Accounts describe the supporting evidence behind each Key Message, the process and rationale authors used in reaching their conclusions, and the author team's expert assessment of the confidence in and, where applicable, likelihood of these conclusions. As such, Traceable Accounts provide information about the state of the science, document sources of uncertainty, identify research gaps, and allow traceability to data and resources.

The Traceable Accounts for each Key Message includes the following sections:

- Description of Evidence Base
- Major Uncertainties and Research Gaps

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- Description of Confidence and Likelihood

The Traceable Accounts could have addressed the statutory requirement that the NCA discuss scientific uncertainties. They could also help satisfy the Executive Order for Restoring Gold Standard Science by addressing reproducibility, transparency, communication of error and uncertainty, and skepticism of findings and assumptions. However, the Traceable Accounts in NCA5's Chapters 2 and 3 are uneven, often superficial and uninformative.

An example of a deficient Traceable Account is NCA5's Key Message 2.2: "Extreme Events are Becoming More Frequent and Severe". The "Description of the Evidence Base" offers two paragraphs, the first summarizing the findings and the second generically describing the types of data that can be used for storms. "Major Uncertainties and Research Gaps" focuses on the uneven distribution across U.S. populations due to differences in exposure and vulnerability. The only limitations in data referred to are the lack of a long-term record of lightning and the lack of homogenized daily and hourly temperature data apart from reanalysis products.

But the most astonishing deficiency is in the "Description of Confidence and Likelihood." One of the statements in Key Message 2.2 is:

> Hurricanes have been intensifying more rapidly since the 1980s (*high confidence*) and causing heavier rainfall and higher storm surges (*high confidence*).

The Description of Confidence and Likelihood includes the following statement:

> Basic physical understanding and climate models both provide robust explanations for the links between climate change and observed changes in these extremes: this is why the authors also have high confidence that storms are delivering more rainfall and high confidence that storm surges are becoming higher.

No reference to journal publications or a specific data set is made anywhere in the chapter regarding hurricane-induced precipitation or storm surge to support this *high confidence* conclusion.

The Traceable Accounts for the various Key Findings of Chapter 3 have some substantial inconsistencies. Consider

> Key Message 3-1: Human activities have caused global warming.
> Confidence and Likelihood: "There is *very high confidence* that emissions of GHGs from human activities, fossil fuel use in particular, have *unequivocally* caused all global warming observed over the industrial era. There is also *very high confidence* that changes in natural climate drivers have had globally small and regionally variable long-term effects over this period."

The Uncertainties section addresses only uncertainties in radiative forcing by greenhouse gases, ignoring the great uncertainty in model responses to that forcing (CWG25 Chapters 4 and 5) In contrast, the Traceability Analysis of Key Message 3-4 ("Humans Are Changing Earth System Processes") raises the problem that relatively little is known about the role of natural variability at the regional scale. From its Description of Evidence Base:

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> In the last decade, there has been increasing recognition of the role of regional-scale natural variability in the past and future evolution of climate, as well as the fact that regional natural variability signals can be competitive with forced anthropogenic signals.

And from its Major Uncertainties and Research Gaps:

> For example, the true natural variability of the climate system on decadal to centennial timescales could be larger than what we estimate from GCMs, which would further increase the irreducible uncertainty stemming from natural variability.

These statements are among the most scientifically credible in the entire NCA5 and they directly undercut the confidence assigned to Key Message 3-1.

There is also a generic problem in tracing NCA5's Traceable Accounts. The Front Matter of NCA5 states:

> Each figure and some tables are accompanied by a metadata survey, which can be accessed in the online version of the report by clicking on the eyeball icon above the figure or table (see the table below for explanations of additional icons used throughout the report). The metadata survey describes data sources, figure or table development methods, copyright information, and other important documentation.

Clicking on the 'eyeball' icon does not reveal the metadata information; instead a "Contact Us" email appears, addressed to the USGCRP. This is an inadequate way to archive the metadata information.

In summary, the Traceable Analyses examined here, with few exceptions, fail to meet the stated objectives of the NCA.

6 Overemphasis on Extreme Scenarios

To respond to the GCRA mandate to "project major trends for the subsequent 25 to 100 years," NCA5 relies on projections of future climate change based on estimates of future emissions (the so-called SSP scenarios) and/or specified levels of radiative forcing (the RCP scenarios). For the most part, NCA5 uses scenarios developed for the IPCC Assessment Reports.

CWG25 Section 3.2.1 presented a critical assessment of past and current IPCC scenario envelopes, showing that they have tended to overshoot observed emissions. IPCC AR6 published in 2021 stated that "The likelihood of high-emission scenarios like RCP8.5 and SSP5-8.5 is considered low in light of recent energy sector developments." and that same year UN Climate Negotiators (COP) stopped using scenarios above 4.5.

NCA5 makes the following observations about the scenarios they use:

> NCA5 authors were advised to assess the full range of scenarios available. (Front Matter)

> Scenarios of future emissions and land-use change are developed as plausible alternatives, but no relative likelihood is attached to them. Some recent studies, however, have argued that

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the highest scenario, SSP5-8.5, is no longer plausible without a reversal of current trends in the adoption of renewables and energy efficiency. (Key Message 3.3 Traceable Analysis)

Despite acknowledging the issue, NCA5 otherwise ignored the problem. A keyword search of mentions of NCA5 RCP/SSP scenarios finds over 50% referred to the extreme emissions scenarios RCP8.5/SSP5-8.5. Further, nine NCA5 figures (5.2, 6.9, 7.4, 11.3, 14.6, 22.13, 22.19, 27.9, 29.13) included *only* the 8.5 scenarios.

The problem of relying on extreme scenarios is particularly acute for NCA5's sea level rise projections. The sea level rise scenarios used in NCA5 do not relate directly to the SSP emissions scenarios, but rather to specified amounts of sea level rise by 2100. Table 4 of NCA5's "Guide to Using this Report" reproduced below shows that Low relates to 0.3 m (0.98 feet), Intermediate-Low relates to 0.5 m (1.64 feet), Intermediate relates to 1.0 m (3.28 feet), Intermediate-High relates to 1.5 m (4.92 feet), and High relates to 2.0 m (6.56 feet).

Table 4. Descriptive Terms for Common Sea Level Rise Scenarios Used in NCA5

Future global mean sea level rise and sea level rise along United States coastline are shown for five scenarios in feet (and meters), relative to a 2000 baseline. The US values shown in the right half of the table are averaged across the US coastal regions, including the contiguous US, Alaska, Hawai'i and the US-Affiliated Pacific Islands, and the US Caribbean. The national values shown in the table differ substantially from regional values. For example, sea level rise is higher in the Gulf Coast and lower or even negative in some parts of Alaska. In the next 30 years (2020–2050), sea level along the contiguous US coasts is expected to rise 0.92 feet (0.28 m), the same amount of sea level rise observed over the last 100 years (1920–2020). See Chapter 9 for regional sea level information. Adapted from Sweet et al. 2022.[7]

Sea Level Rise Scenario Descriptor	Global Mean Sea Level			United States		
Year	2050	2100	2150	2050	2100	2150
Low	0.49 (0.15)	0.98 (0.3)	1.31 (0.4)	0.59 (0.18)	0.98 (0.3)	1.64 (0.5)
Intermediate-Low	0.66 (0.20)	1.64 (0.5)	2.62 (0.8)	0.75 (0.23)	1.64 (0.5)	2.95 (0.9)
Intermediate	0.92 (0.28)	3.28 (1.0)	6.23 (1.9)	0.89 (0.27)	3.28 (1.0)	6.89 (2.1)
Intermediate-High	1.21 (0.37)	4.92 (1.5)	8.86 (2.7)	1.12 (0.34)	4.92 (1.5)	8.86 (2.7)
High	1.41 (0.43)	6.56 (2.0)	12.14 (3.7)	1.38 (0.42)	6.56 (2.0)	12.46 (3.8)

TABLE 1: Reproduction of Table 4 from the Front Matter of NCA5

Considering only projections representing processes quantified with at least medium confidence, IPCC AR6 assessed global mean sea level projections for all emissions scenarios (including implausible extreme emissions scenarios) for 2100 to fall between 0.2 and 1.6 m (5th—95th percentile range). By contrast, the range of sea level rise scenarios considered by NCA5 extends to 2.0 m. Further, NCA5 fails to include plausible lower scenarios, such as 0.2 m cited by the IPCC, which also corresponds to the average rate of sea level rise over the past century.

Chapter 9 of NCA5 offers the following predictions of sea level rise:

> "Under a range of potential global warming levels, average sea level along US coastlines is *likely* to be between 12 and 20 inches above 2000 sea levels in 2050 (Figure 9.2)."

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The observed global sea level rise from 2000-2024 is only approximately 3.4 inches (0.28 feet). NCA5 is thus projecting a sea level rise during 2025 and 2050 along U.S. coasts that is 2.5 to 4.9 times the global rate observed during 2000-2024, an exceedingly implausible outcome. Chapter 9 further states:

> "There is *high confidence* and it is *likely* that sea levels will rise about 11 inches (likely range of about 9–13 inches) between 2020 and 2050"

This implies a rate of increase more than double the rate from 2000 to 2024, again an implausible outlook. In summary, NCA5 presents future sea level rise scenarios that are not directly relatable to either SSP/RCP emissions scenarios or to plausible global warming levels. The NCA5 scenarios include two that are higher than the 95th percentile for the extreme emissions scenario RCP8.5 and include hypothesized ice sheet processes in which there is low confidence. Projections to 2050 require rates of sea level rise from 2025 to 2050 that are more than double the rate observed during 2000-2024. Further, NCA5 ascribes *high confidence* to these sea level rise projections. CWG25 Section 7.3 provides further context for USGCRP projections of extraordinary sea level rise in the next 25 years.

More generally, NCA5's inclusion of, and even focus on, implausible extreme scenarios creates projections of alarming impacts that are very unlikely to be driven by anthropogenic warming.

7 Conflation of Natural and Anthropogenic Climate Changes

NCA5's Glossary defines "climate change" as a change in climate for any reason. This is technically correct, but at variance with IPCC usage, which also corresponds to the popular connotation, in which the term refers specifically to anthropogenically-caused change. The distinction is not academic- it is central both to attribution questions and to projections, since anthropogenic changes depend on emission rates, while natural changes are unavoidable. Having defined climate change broadly NCA5 then fails to distinguish natural and anthropogenic changes in context with the effect of implicitly over-attributing changes to greenhouse gas emissions.

The discussion on NCA5 page 2-4 begins "Human activities are changing the climate", then goes on to list evidence for anthropogenic GHG emissions and climate warming. The next paragraph begins "Climate change is happening now in the United States. Including Alaska, the continental US has been warming about 60% faster than the planet as a whole since 1970." The implication is that the warming of CONUS faster than the planetary average is an effect of GHG emissions. But it is an artifact of the Earth's surface being 70 percent ocean. Since the ocean warms more slowly than land, comparison of any land surface outside the tropics with the global average would show the land surface to be warming faster than the global average, regardless of the cause of the warming.

The same page goes on to say "Climate change is already affecting people in the United States. Extreme heat was estimated to be responsible for more than 700 deaths per year between 2004 and 2018 although some estimates put heat-related mortality closer to 1,300 deaths annually." But extreme heat has always occurred naturally, and whether natural or not, it has always been a risk to human health. As to trends, the data show that adaptation has caused the mortality burden of extreme heat to drop substantially in recent decades (CWG25 Section 10.3.1).

Consider also the NCA5 statement on precipitation cited in Section 3.2:

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> Many eastern regions of the country are getting wetter (Figure 2.4). Average annual precipitation from 2002-2021 was 5%-15% higher relative to the 1901-1960 average in the central and eastern US, a trend attributable to climate change.

The attribution is superfluous because the statement is a tautology by NCA5's definition of climate change. Its gratuitous inclusion effectively attributes the observed trend to greenhouse gas emissions.

Exploitation of the ambiguity inherent in the term "climate change" is endemic to NCA5. The NASEM review (pp. 23-24) flagged this problem as follows:

> The draft NCA5 report frequently describes "change" but does not consistently distinguish between natural variability and climate change. This lack of clarity can be misleading for the reader by creating the misconception that some impacts that are the result of the combination of natural variability and climate change are instead solely due to climate change... it is important for NCA5 authors to accurately identify the multiple drivers of change (including global change), in addition to climate change, and accurately attribute impacts. Clearly describing impacts due to natural variability, climate change, or a combination of the two is important not only for informing policy decisions, but also for building public understand [sic] and trust in the report's messages. Climate change and natural variability should be clearly defined in the glossary and natural variability could be introduced in chapter introductions when the concept is important for understanding key messages.

This could have been easily addressed, for example by reserving the term "climate change" for anthropogenic changes and using "climate variability" for natural changes. But the NCA5 authors seemingly ignored the recommendation.

A separate but related issue is use of the term "climate change" to refer to increases in socioeconomic vulnerabilities that have anthropogenic causes unrelated to GHGs. NCA5 page 1-19 states "Climate change exacerbates inequalities." But the issue discussed is the negative correlation between neighborhood-level income and land surface temperatures in urban areas. To the extent the correlation is real, the most likely explanation is that low-income households concentrate where housing is less expensive, which might be in neighborhoods with less nearby parkland and tree cover; that has nothing to do with CO_2 emissions.

8 Summary Evaluation of NCA5 and Recommendations for NCA6

This chapter summarizes our evaluation of NCA5 relative to OSTP's charge: whether NCA5 (1) complied with the USGCRP's statutory obligation; (2) adheres to the core tenets of Gold Standard Science; and (3) can suitably inform federal climate and energy policy. The points made in this summary analysis refer to specific sections of this report as well as to the CWG25 report.

8.1 Compliance with USGCRP's statutory obligation

As cited in Section 1.2 of this report, the Global Change Research Act requires an assessment that:

> (1) integrates, evaluates, and interprets the findings of the [Global Change Research] Program and discusses the scientific uncertainties associated with such findings;

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(2) analyzes the effects of global change on the natural environment, agriculture, energy production and use, land and water resources, transportation, human health and welfare, human social systems, and biological diversity; and
(3) analyzes current trends in global change, both human-induced and natural, and projects major trends for the subsequent 25 to 100 years.

We deem NCA5 to have fallen short when evaluated against these criteria because of the following major shortcomings (see indicated section for details):

- Inadequate assessment of the relevant topics in climate science and the hazard components of climate impacts (such as hurricanes and floods). NCA5 instead focuses on evaluation of societal vulnerabilities (such as flood infrastructure, access to air conditioning, etc.), "Climate Action," and policy recommendations with a social justice emphasis (Chapter 2).
- Overconfidence in conclusions and inadequate assessment of uncertainties (Chapter 3)
- Inadequate discrimination between natural and human-induced causes of trends and impacts (Chapter 7)
- Inadequate analysis of climate trends by relying on short time periods (Chapter 6)
- Uncritical evaluation of emission scenarios and climate model simulations in making projections for the next 25 to 100 years (Chapter 6).

8.2 Adherence to the tenets of Gold Standard Science

With respect to the tenets of Gold Standard science listed in Section 1.3 of this report, we have identified the following major shortcomings in NCA5:

- **Lack of reproducibility.** In the few examples that we examined closely, we identified an instance where we could not reproduce the findings of the NCA5, a task that should require only rudimentary data analysis (Section 4.1)
- **Lack of transparency.** In many instances, the Traceable Account fails to justify the Key Finding. Metadata was not readily accessible. (Chapter 5)
- **Inadequate communication of error and uncertainty.** The Traceable Account for each Key Message provides a section on Major Uncertainties and Research Gaps; most of the accounts that we examined were superficial and uninformative. (Chapter 5)
- **Not skeptical of findings and assumptions.** The main text of the chapters is, with few exceptions, not skeptical of its findings and assumptions and does not mention dissent or disagreement. (Chapters 3 and 5)
- **Some hypotheses and Key Messages are not falsifiable.** Key Message 13.4 is but one of many examples: "Equitable Distribution of Transportation Trade-offs and Benefits Requires Community Involvement." See discussion in Chapter 2.
- **Assumption that all changes are harmful** due to warming and additional atmospheric CO_2 (Chapter 2)
- **Inadequacy of the peer review process.** The review of the NCA5 Third Order Draft by National Academies of Science, Engineering and Medicine (NASEM) identified some of the deficiencies we have noted, but the NCA5 authors were not obligated to adopt the NASEM recommendations. More importantly, we've identified many other deficiencies in NCA5; the NASEM review did not point them out and thus lacked the rigor expected of NASEM reports.

8.3 Suitability for informing Federal climate and energy policy

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We assess that the selection and presentation of information in NCA5 makes it an unreliable basis for U.S. climate and energy policy making. For each of the elements of knowledge characterization suitable for risk management listed in Section 1.3, here are specific examples where NCA5 falls short:

- The degree to which the assumptions made are reasonable/realistic based on background knowledge
    - NCA5 focused on implausibly extreme scenarios for emissions and sea level rise and made policy recommendations without adequate consideration of the costs
- The degree to which data/information exists and are reliable and relevant
    - NCA5's unjustified assumptions about model reliability, and its use of short time periods for analysis, does not support its high-confidence conclusions
- The degree to which there is disagreement among experts, including those from different environments or academic fields
    - While NCA5 was an interdisciplinary effort, the concerns we have raised all point to a failure to canvass or communicate the full range of evidence, including data and research findings that speak against Key Messages.
- The degree to which the phenomena involved are understood and accurate models exist
    - NCA5 is not appropriately skeptical of the ability of climate models to attribute the causes of warming and extreme events or to project future climates, especially at the regional level
- The degree to which the knowledge has been thoroughly examined with respect to unknown knowns
    - A major NCA5 shortcoming is its dismissal of natural climate variability in many contexts where it should have been a major consideration

NCA5 is also problematic for informing policy because by describing everything everywhere as threatened by climate change, frequently with exaggerated language, it fails to provide guidance for policymakers who need to prioritize and allocate scarce resources for adaptation and risk management. Likewise, it advocates for ambitious mitigation policies without a proper analysis of risks and costs. The NASEM Review of the NCA5 underscores the endemic nature of this problem - their review appears to be written by authors who share many of the biases of the NCA5 team, with an inordinate focus on social and policy issues.

NCA4 was in some respects a better policy-informing assessment than NCA5. It offered a more thorough consideration of climate science, consistently used data back to 1901, and had less of an advocacy tone. But it too engaged in some misleading hyperbole, for example in its presentation of heat extremes. NCA4's Part I said (prominently and with *Very High Confidence*) on Page 19 of the Executive Summary:

> There have been marked changes in temperature extremes across the contiguous United States. The number of high temperature records set in the past two decades far exceeds the number of low temperature records.

and offered this figure in support:

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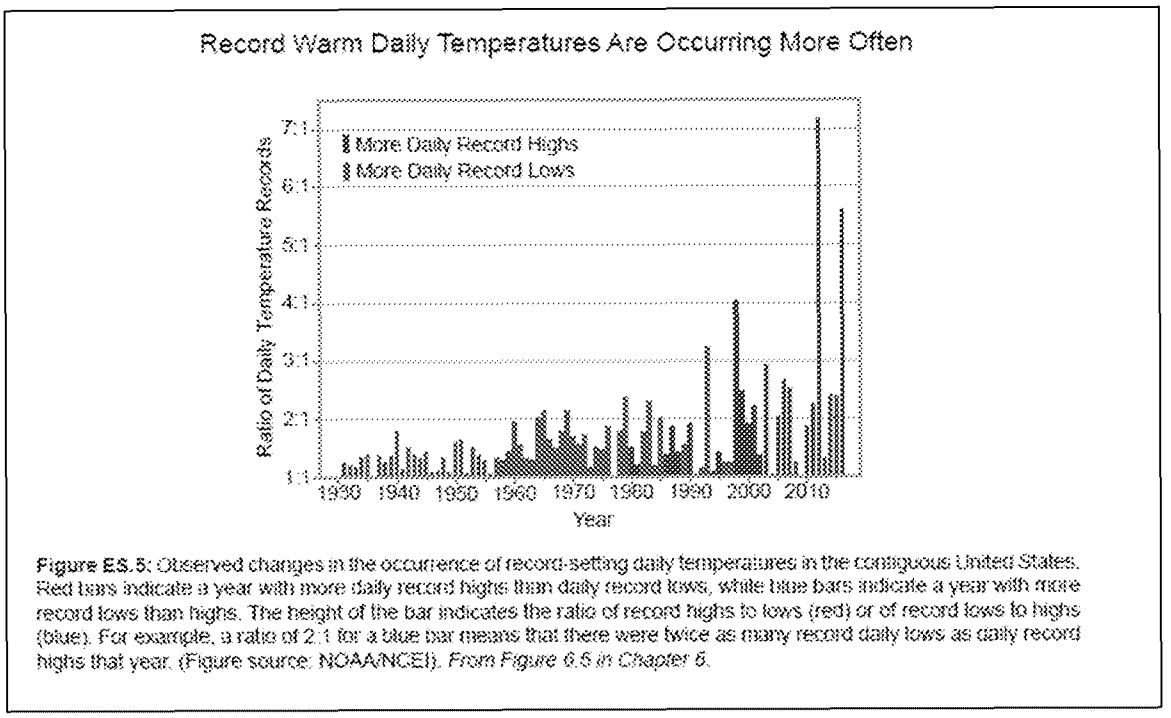

Figure ES.5: Observed changes in the occurrence of record-setting daily temperatures in the contiguous United States. Red bars indicate a year with more daily record highs than daily record lows, while blue bars indicate a year with more record lows than highs. The height of the bar indicates the ratio of record highs to lows (red) or of record lows to highs (blue). For example, a ratio of 2:1 for a blue bar means that there were twice as many record daily lows as daily record highs that year. (Figure source: NOAA/NCEI). *From Figure 6.5 in Chapter 6.*

FIGURE 5: Reproduction of Figure ES.5 from NCA4

The figure appears to show that record warm daily temperatures are occurring more often. But the underlying data (see CWG Figure 6.3.3) show the opposite: extreme heat in the U.S. peaked in the 1920s and 1930s and declined thereafter. Despite its misleading title, what Figure ES.5 shows is the *ratio* of annual warm and cold event counts. Both types of extremes declined over the sample interval, but cold events declined more than warm ones, so the ratio went up. By graphing the ratio instead of simple counts, NCA4 created a visual impression opposite to what is in the data.

NCA4 also shares with NCA5 the tendency to describe everything everywhere as under threat from climate change, undermining its usefulness for policymakers. For instance, while it contains a chapter on potential adaptation responses (Volume 2 Chapter 28) it downplays the value of such planning by stating as Key Message 2 (p. 1310) that "Climate change outpaces adaptation planning: Successful adaptation has been hindered by the assumption that climate conditions are and will be similar to those in the past."

8.4 NCA5 and the 2025 Texas Floods

To the extent an NCA should assist regional policymakers set priorities for future disaster management, we can look back at NCA4 and NCA5 and ask what relevant information they provided for the Texas Hill Country, where the tragic events of July 2025 took place. We first note that while the region in question is historically prone to flooding, the Environmental Protection Agency Climate Change Indicators record[2] shows decreasing flood frequency and magnitude since 1965 in that region; in other words the flood risk predates anthropogenic climate change and is not apparently exacerbated by it. Likewise daily precipitation records for nearby Austin are available back to 1873 and show no increase in annual average or maximum precipitation (see CWG25 Section 6.4 for links

[2] See https://www.epa.gov/climate-indicators/climate-change-indicators-river-flooding

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to data). Hence the key contribution an NCA could make is explaining the historical context of extreme rainfall events and flood risks, rather than speculations about far future changes that might occur.

The NCA4 section on the Southern great Plains states that precipitation trends are not clearly attributed to anthropogenic forcing (pp. 213-214) and that "no formal attribution of observed flooding changes to anthropogenic forcing has been claimed" (p. 241). This supports the view that the focus of resource allocation should be adapting to the known current risk profiles of the Hill Country and that there is little to be gained by trying to forecast changes under greenhouse forcing, nor would GHG emission reductions be an effective way to reduce future flood risks. However, as noted above, NCA4 undermines its own usefulness by claiming in Volume 2 Chapter 28 that climate change is happening so quickly that historical data is uninformative for planning purposes.

NCA5 presents no data on precipitation patterns in the Southern Great Plains and no information on specific high risk zones. Instead it makes sweeping unsubstantiated claims to the effect that every climate risk is getting worse over time. For example, in Chapter 26 (Southern Great Plains) the first Key Message is (p. 26-7):

> Climate change is beginning to alter how we live in the Southern Great Plains, putting us at risk from climate hazards that degrade our lands and waters, quality of life, health and well-being, and cultural interconnectedness (*high confidence*). Many climate hazards are expected to become more frequent, intense, or prolonged; to broaden in spatial extent; and to result in more people experiencing costly, deadly, or stressful climate-related conditions (*very likely, high confidence*). To address the growing risk, effective climate-resilient actions include implementing nature-based solutions; valuing Indigenous, traditional, and local knowledges; and infusing climate change solutions into community planning (*medium confidence*).

This is both inaccurate and useless for local authorities charged with setting priorities and making resource allocation decisions. The same chapter presents rainfall projections through the mid-21st century (Figure 26.10) that imply drying thoughout southern TX, but no explanation is given as to how this reconciles with projections elsewhere in NCA5 (Figure 2.12 p. 2-25) of increasing extreme precipitation in the same region. The first discussion of regional trends in heavy rainfall events is on page 26-22 which focuses entirely on sports teams having to move events indoors which results in "increasing participation costs and decreasing access to sports, especially for lower-income populations." ~~Adaptation advice consists of the following cartoon on page 26-19:~~ DELETE THIS FIGURE, DOESN"T BELONG IN CONCLUSIONS CHAPTER

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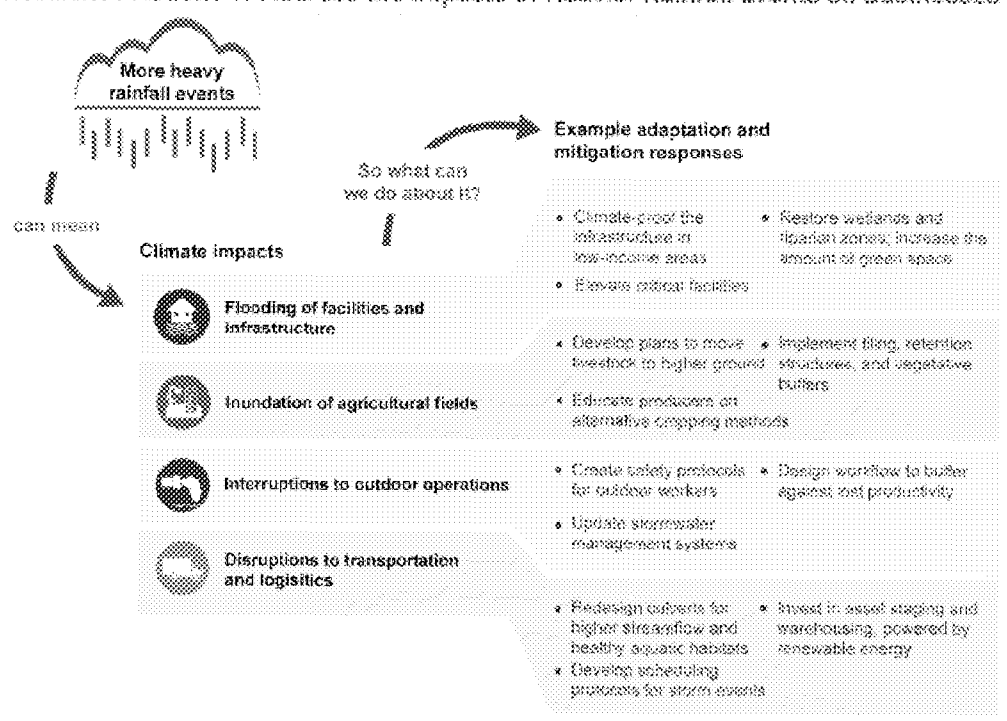

Figure 26.11. An increased number of heavy rainfall events affects business and industry across the Southern Great Plains through flooding of facilities and infrastructure, inundation of agricultural fields, interruptions to outdoor operations, and disruptions to transportation and logistics. The example adaptation and mitigation actions can increase resilience and reduce negative impacts. Figure credit: See figure metadata for contributors.

~~FIGURE 6: screenshot of NCA5 Figure 26.11~~

~~The advice is so vacuous it could have been written by someone who has never studied the topic. Combined with pervasive advocacy for renewable energy NCA5 was worse than simply unhelpful: if planners based serious decisions on it they would have misallocated resources away from potentially beneficial measures towards worthless ones.~~ A BIT SNARKY, the ABOVE TEXT SPEAKS FOR ITSELF

8.5 Recommendations for NCA6

While we have assessed NCA5 to be scientifically inadequate and unsuitable as a basis for decision-making, one can imagine a different National Climate Assessment that meets statutory and policymaker requirements. The goal should be not to persuade, but to impart understanding by being objective, transparent and complete. A suitable NCA would be an important complement to IPCC assessments to the extent that its analysis and conclusions differ where appropriate from the "consensus" of the IPCC reports and additional topics are addressed. Such a report would promote a more open scientific discussion and a more informed policy debate.

We recommend that the NCA6 have a narrower scope than NCA5, refocusing on climate science, including natural climate variability, with topics to include:

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- How the climate has varied in the past. The U.S. has the best and longest meteorological records and they should be examined and displayed in their entirety. Trend analyses should include longest periods available and employ suitable statistical methods. Local paleoclimate data should be considered where available. Analysis should demonstrate not only how the climate has varied and changed, but also regional heterogeneity. Standard, easily understandable metrics should be employed.
- The range of climatic and weather conditions, including extremes, that have occurred in the past and can reasonably be expected to occur in U.S. regions over the near future.
- A critical survey of current global and regional modeling capabilities and their suitability for regional impact assessments and projections. This would include an assessment of their ability to reproduce observed changes. It should also discuss alternative methods for generating scenario projections on regional and decadal scales, along the lines of Chapter 10 of the IPCC AR6 WGI Report.
- Assessment of the impacts of recent historical climate variability and change on ecosystems and society. Where long-term data indicate a detectable regional change, regional projections can be made for the period 2030-2050. Emissions scenarios exceeding RCP4.5/SSP2-4.5 and ECS values exceeding 4°C should not be used. Regional projections to 2100 have no credibility at this time and so should not be included in NCA6.

It is important that climate projections be assessed in context of current science capabilities. The pressures toward spatially or temporally precise projections should be resisted as the current models are not up to the task (an example is discussed in CWG25 Section 5.8). In that light, the many pages of NCA5 devoted to projected regional and sectoral impacts have little value.

A key effort that would aid NCA6 would be the development of more complete and accurate observational datasets, including daily US surface temperature and precipitation, from which to more accurately assess changes in properties such as extremes since the 19th century. CWG25 put considerable effort into creating such time series to overcome misleading information now contained in the official NOAA quality-controlled datasets utilized in the NCAs and by climate analysts in general. Examples of deficiencies in current, official datasets are given in supplementary material here [Link] which motivate this recommendation.

Given the substantial deficiencies and biases in NCA5 that we have identified, producing an objective NCA6 report with the current NCA organizational construct would be a challenge. A NASEM review could help, but only if the selected participants reflect full viewpoint diversity and do not simply mirror the assumptions and biases of past NCA teams. We regard the CWG25 report to be a good start on NCA6 in terms of scope and objectivity, including adherence to the tenets of Gold Standard Science.

More broadly, we recommend a rewrite of the Global Change Research Act. The current mandate is vague and off point, allowing successive NCA teams to interpret the mandate as they see fit. Moreover, it is becoming increasingly clear that current and foreseeable models are not fit-for-purpose to describe regional climates, let alone usefully project them for 25 to 100 years. Further, the use of the term "global change" is ambiguous and outdated.

9 REFERENCES

DOJ_00000874

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10 APPENDIX: CHARGE TO THE REVIEW

DOJ_00000876

ABOUT THE AUTHORS

[Insert updated bios]

DOJ_00000877

Supporting evidence for revisiting and revising the NOAA climate data archive for NCA6.

In support of the recommendation to revisit the NOAA/NCEI official, quality-controlled datasets we show two examples that directly relate to determining changes in extremes over long periods. Aside from the fact that considerable station data have yet to be keyed into computer-readable files, is the overly sensitive nature of the quality-control algorithms that search for and eliminate data that were judged to be erroneous, but in fact were accurate. As would be expected, extreme values are unfortunately natural targets for such algorithms. Two examples follow.

An Example of Temperature Problems, Newport OR

When searching for the top ten extreme high temperatures in the NOAA database for Newport OR on the Pacific Coast the results returned are listed in Table 1.

Rank	Temperature °F	Date
1	94.0	1980-10-02
2	91.0	1993-09-26
-	91.0	1981-09-06
-	91.0	1957-09-22
5	90.0	1985-06-17
-	90.0	1962-09-17
-	90.0	1907-10-09
8	89.0	2006-09-02
-	89.0	1976-09-09
-	89.0	1975-09-21

Table 1. Results returned from the NOAA quality-controlled database when queried on 18 July 2025 for the ten hottest daily temperature values in Newport OR. https://scacis.rcc-acis.org

However, in our effort to replace missing values so as to provide the most complete datasets for various analyses, several Newport temperatures above 94°F were discovered but listed as missing in the database, mostly in the early part of the record. The quality-control algorithm apparently determined that these values exceeded certain criteria.

Below in Fig. 1 is the actual form for June 1925 in Newport indicating the temperature on 24 June reached 100°F, exceeding the "official" hottest value by 6 °F. The entry on the 24th is accompanied by the wind direction of easterly, "E", which is the classic case of offshore wind producing extreme temperatures. Other stations nearby had excessively high temperatures as well, yet the algorithm determined Newport's 100 °F to be erroneous. In the dataset utilized in CWG25, we replaced many of these "missings" with observed values which provided us a better (not perfect) indication of the distribution of extreme events through time (see Figs. 6.3.3 to 6.3.6 in CWG25).

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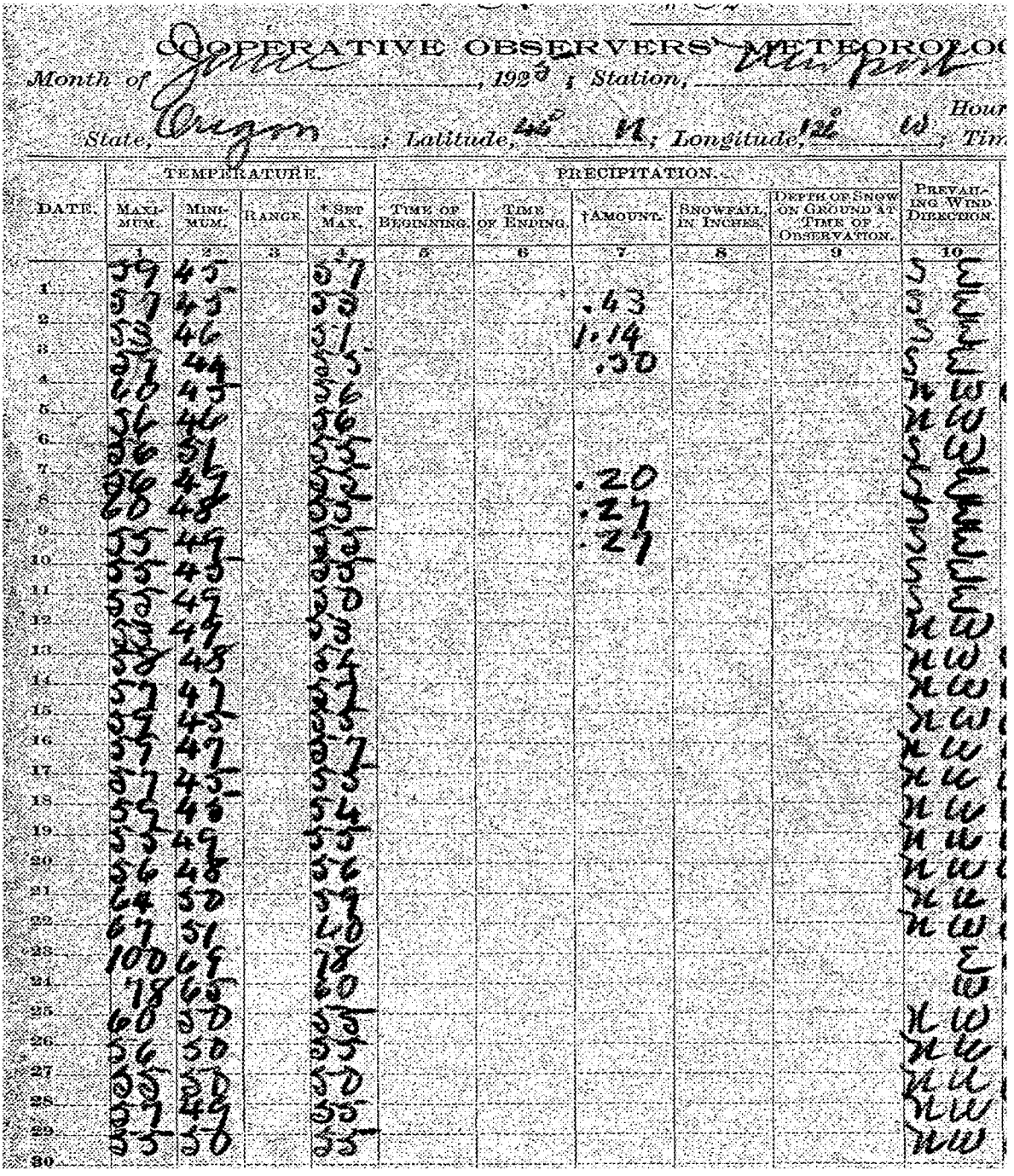

COOPERATIVE OBSERVERS' METEOROLO

Month of June, 192[illegible]; Station, Newport

State, Oregon; Latitude, 44° N; Longitude, 124° W; Hour; Tim

DATE.	TEMPERATURE.				PRECIPITATION.					PREVAILING WIND DIRECTION.
	MAXIMUM.	MINIMUM.	RANGE.	*SET MAX.	TIME OF BEGINNING.	TIME OF ENDING.	†AMOUNT.	SNOWFALL IN INCHES.	DEPTH OF SNOW ON GROUND AT TIME OF OBSERVATION.	
	1	2	3	4	5	6	7	8	9	10
1	57	43		57						W
2	57	45		57			.43			W
3	56	46		56			1.14			W
4	60	44		56			.30			W
5	56	46		56						W
6	56	50		56						W
7	56	47		56						W
8	60	48		56			.20			W
9	55	47		56			.27			W
10	55	45		56			.27			W
11	55	47		56						W
12	56	49		56						W
13	56	48		56						W
14	56	47		56						W
15	56	47		56						W
16	56	47		56						W
17	56	47		56						W
18	56	48		56						W
19	56	49		56						W
20	56	48		56						W
21	56	50		56						W
22	67	51		60						W
23	100	64		78						E
24	78	60		60						W
25	60	50		56						W
26	56	50		56						W
27	56	50		56						W
28	56	49		56						W
29	56	50		56						W
30										

Figure 1. Cooperative Observer's Form for Newport OR (COOP ID 356032), June 1925. Note the 100°F reading on the 24th is listed as missing in the NOAA/NCEI "quality controlled" public datafiles.

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An example of Precipitation Problems, Holdenville 2SSE OK.

As with our temperature datasets, we replaced missing daily precipitation data with observed values. If the data were missing for the particular station, we substituted the values from a nearby station. In the case of Holdenville 2SSE OK, a number of missing values appeared in the NOAA quality-controlled archive that otherwise were known to have been recorded by the observer. Table 2 lists the daily rainfall for Holdenville 2SSE for July 1950 from the "quality-controlled" NOAA archive and from the actual form (similar to Fig. 1).

Year	Month	Day	NOAA Q-C	COOP FORM
1950	7	1	0	0
	7	2	0	0
	7	3	0.02	0.02
	7	4	0.22	0.22
	7	5	0.59	0.59
	7	6	0	0
	7	7	0	0
	7	8	0	0
	7	9	0.22	0.22
	7	10	M	4.55
	7	11	0	0
	7	12	0	0
	7	13	0.04	0.04
	7	14	0.05	0.05
	7	15	0	0
	7	16	0	0
	7	17	M	2.87
	7	18	0	0
	7	19	0	0
	7	20	1.1	1.1
	7	21	M	2.95
	7	22	1.3	1.3
	7	23	0	0
	7	24	0	0
	7	25	1.39	1.39
	7	26	0	0
	7	27	0	0
	7	28	0.11	0.11
	7	29	1.02	1.02
	7	30	0.18	0.18
	7	31	0.09	0.09

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Table 2. Daily precipitation values for Holdenville 2SSE OK (COOP ID 344235), July 1950. The official NOAA Q-C values are those that scientists and the public receive. The last column contains the values recorded by the observer on the original form. Note the three days of heaviest rainfall are set to "missing" in the official archive but are clearly recorded on the observer's form (red).

Stations near Holdenville also recorded excessive rainfall on the three days indicated as missing, so the evidence is substantial that the observer recorded accurate daily totals. This has bearing on the calculations of extreme events. A query of the NOAA database for extreme monthly precipitation indicates the value according to the observer's form (16.70") would have been the wettest July in the entire record, and fourth highest of all months (queried on 18 July 2025). However, because July 1950 has only three "missing" days, its monthly total is considered valid at 6.33" so it does not appear on the list of extreme monthly totals. [The precipitation stations utilized in CWG25 Figs. 6.4.1 to 6.4.5 and in this Review of NCA5 were all serially complete.]

There are many other such cases, but these two serve as examples to motivate our recommendation for NOAA to revisit their datasets to develop accurate, complete-as-possible, long-term time series of daily meteorological variables from the Cooperative Observers forms and other sources. This requires a combination of AI techniques and the experience of trained climatologists to discern whether values are legitimate or truly erroneous (of which there are also many). This is a tedious process but one that ultimately provides scientists and the public with the type of information needed to confidently assess threat levels of various rarely-observed weather phenomenon and how they may be changing through time.

DOJ_00000881

From: Judith Curry <curry.judith@gmail.com>
Sent: Friday, July 18, 2025 12:26 PM
To: Ross McKitrick
Cc: John Christy; Roy Spencer; Steven Koonin; Travis Fisher; Josh Loucks; Seth Cohen
Subject: Re: NCA5 progress

I suspect FEMA isn't one of USGCRP agencies. Also probably not USACE. IMO, NCA should be targeted at those orgs

On Fri, Jul 18, 2025 at 8:31 AM Ross McKitrick <ross.mckitrick@gmail.com> wrote:
That's excellent. I'd be interested in someone at FEMA providing feedback on our NCA report.

On Fri, Jul 18, 2025 at 9:50 AM John Christy <climateman60@gmail.com> wrote:
A couple of my folks did a quick write up of the TX floods.

https://www.earthdata.nasa.gov/dashboard/stories/tx-flood

John C.

On Fri, Jul 18, 2025 at 9:22 AM Judith Curry <curry.judith@gmail.com> wrote:
Thoughts on turning section 8.4 into a separate chapter, e.g.

8. Regional example: Texas 2025 floods

9. Conclusions and recommendations for NCA6

On Fri, Jul 18, 2025 at 3:28 AM Roy Spencer <roywspencer@hotmail.com> wrote:
I've added several edits to Judy's version (attached).

-Roy

From: Steven Koonin <steven.koonin@gmail.com>
Sent: Wednesday, July 16, 2025 5:29 AM
To: 'Judith Curry' <curry.judith@gmail.com>; 'Ross McKitrick' <ross.mckitrick@gmail.com>
Cc: 'John Christy' <climateman60@gmail.com>; 'Travis Fisher' <travis.scott.fisher@gmail.com>; 'Roy W. Spencer' <roywspencer@hotmail.com>; 'Josh Loucks' <loucksj14@gmail.com>; 'Seth Cohen' <seth.cohen@hg.doe.gov>
Subject: RE: NCA5 progress

And my further edits attached.

Do keep me at least cc'd over the next few days – I'll respond as I'm able.

SEK

From: Judith Curry <curry.judith@gmail.com>
Sent: Tuesday, July 15, 2025 7:05 PM
To: Ross McKitrick <ross.mckitrick@gmail.com>
Cc: John Christy <climateman60@gmail.com>; Steven Koonin <steven.koonin@gmail.com>; Travis Fisher <travis.scott.fisher@gmail.com>; Roy W. Spencer <roywspencer@hotmail.com>; Josh Loucks <loucksj14@gmail.com>; Seth Cohen <seth.cohen@hq.doe.gov>
Subject: Re: NCA5 progress

Here is my revised version. One proposed change of substance, relates to TX floods.

In section 8.3, i proposed modifying one of the bullets:

- The range of climatic and weather conditions, including extremes, that have occurred in the past and can reasonably be expected to occur in U.S. regions over the near future. An example of a salient acute failure is the NCA5 chapter {region that includesTexas} that fails to mention the historical occurrence and future risk of flash floods in the Texas Hill Country ROSS MAYBE MENTION WHAT NCA5 SAID ABOUT TX FLOODS in REGIONAL CHAPTER, THEN INCLUDE LINK TO YOUR MINI ANALYSIS

An alternative approach would be to add a new chapter on Failure to document the risk of extreme events based on the historical data base, something like that. Simpler just to mention it in Section 8.3

On Tue, Jul 15, 2025 at 3:33 PM Ross McKitrick <ross.mckitrick@gmail.com> wrote:

> If Steve's away until Tuesday a Friday July 18 deadline won't be feasible, so let's work towards a Friday July 25 deadline.
>
> I propose this week we go in the following order to prevent us working on overlapping drafts
>
> Judy goes through the draft tonight
>
> Steve has another look tomorrow.

Then Roy, then John, then me.

On Tue, Jul 15, 2025 at 3:47 PM John Christy <climateman60@gmail.com> wrote:

I like Judy's idea. It's one way to avoid going through the preparation and experience of something like a colonoscopy twice in one month.

John C.

On Tue, Jul 15, 2025 at 2:12 PM Judith Curry <curry.judith@gmail.com> wrote:

Here is a way around the NCA4 issue, propose adding the following text to end of section 8.3

NCA4 provided a better assessment than NCA5 in terms of a more thorough consideration climate science, use of data back to 1901, and less of an advocacy tone. However, NCA4 shared the following endemic problems with NCA5

- Overconfidence in conclusions
- Inadequate treatment of natural variability
- Inadequate Traceable Accounts and communication of uncertainty
- Over reliance on extreme scenarios

On Tue, Jul 15, 2025 at 12:02 PM Steven Koonin <steven.koonin@gmail.com> wrote:

Just a heads up that I will be on the West Coast with very limited connectivity from tomorrow (Wednesday) evening through Monday evening (West Coast times). Back on the East Coast early Tuesday morning.

SEK

From: Travis Fisher <travis.scott.fisher@gmail.com>
Sent: Tuesday, July 15, 2025 1:47 PM
To: Steven Koonin <steven.koonin@gmail.com>
Cc: Judith Curry <curry.judith@gmail.com>; Ross McKitrick <ross.mckitrick@gmail.com>; John Christy <climateman60@gmail.com>; Roy W. Spencer <roywspencer@hotmail.com>; Josh Loucks <loucksj14@gmail.com>; Seth Cohen <seth.cohen@hq.doe.gov>
Subject: Re: NCA5 progress

Hi all,

If we need to move quickly to publish the NCA critique as a DOE product, what would be a reasonable date for us to consider it final from the authors' point of view (subject to internal review for errors but not subject to political meddling)? I have to build a publication schedule, and I'd like to work backward from a date that's comfortable for you all.

I ask because the political powers that be are interested in having a published version to cite. Sooner is better, of course, but I don't want to jam you up. They certainly want it to be published before we could conceivably have a new head of the USGCRP, so it will have to be a DOE report.

Finally, if you're considering critiquing the entire NCA apparatus and previous reports, I think that would be helpful. The political response to an NCA5 critique so far has been (I'm paraphrasing), "Even if we show that NCA5 is not a solid basis for policymaking, what about NCA4 and prior reports?"

As always, please feel free to call me or convene a meeting if you want to discuss anything. I'll also try to keep everyone posted as the CWG report moves through the necessary hoops.

Best,

Travis

On Tue, Jul 15, 2025 at 11:41 AM Steven Koonin <steven.koonin@gmail.com> wrote:

> I've marked up Judy's "desnarked" version (attached). Mostly typos and wording, but a few issues of substance. And still on the fence about whether and how to include the NCA4 story on temperature extremes.

SEK

From: Judith Curry <curry.judith@gmail.com>

Sent: Sunday, July 13, 2025 3:12 PM
To: Ross McKitrick <ross.mckitrick@gmail.com>
Cc: Steven Koonin <steven.koonin@gmail.com>; John Christy <climateman60@gmail.com>; Roy W. Spencer <roywspencer@hotmail.com>; Travis Fisher <travis.scott.fisher@gmail.com>; Josh Loucks <loucksj14@gmail.com>; Seth Cohen <seth.cohen@hq.doe.gov>
Subject: Re: NCA5 progress

see attached for a shorter, desnarked version of NCA5 for you to consider. I didn't do track changes, its clean text

On Sun, Jul 13, 2025 at 10:55 AM Ross McKitrick <ross.mckitrick@gmail.com> wrote:

> Steve- this is the most recent version I have. There is also a Supplement on precip trends.

On Sat, Jul 12, 2025 at 6:18 PM Steven Koonin <steven.koonin@gmail.com> wrote:

> Ross- Can you send around the most recent version of the NCA5 review. I can't seem to identify it in the emails and would like to go through it again in the next few days.
>
> SEK

From: Ross McKitrick <ross.mckitrick@gmail.com>
Sent: Friday, July 11, 2025 3:49 PM
To: John Christy <climateman60@gmail.com>
Cc: judith curry <curry.judith@gmail.com>; Roy W. Spencer <roywspencer@hotmail.com>; Steven Koonin <steven.koonin@gmail.com>; Travis Fisher <travis.scott.fisher@gmail.com>; Josh Loucks <loucksj14@gmail.com>; Seth Cohen <seth.cohen@hq.doe.gov>
Subject: Re: NCA5 progress

John and I only appear in Section 4.1 as part of challenging the reproducibility of the NCA5 Key Message regarding precipitation. 2 of our 3 citations in the reference list are data archives which are there for transparency purposes.

On Fri, Jul 11, 2025 at 2:53 PM John Christy <climateman60@gmail.com> wrote:

> Judy
>
> I must be missing something. Our papers directly address the issues espoused by NCA5. We offer all the data and methods. Why should our work be suppressed?
>
> John C.
>
> Sent from my iPhone
>
> > On Jul 11, 2025, at 1:16 PM, judith curry <curry.judith@gmail.com> wrote:
> >
> > We need to think about our audience who we want to reach and influence. We don't want this to be another salvo in the climate wars. But to rise above it and be hyper objective.
> >
> > Sent from my iPhone
> >
> > > On Jul 11, 2025, at 10:07 AM, John Christy <climateman60@gmail.com> wrote:
> > >
> > > Judy
> > >
> > > ... Christy, McKitrick and Koonin ... you could look at it this way: we're the only ones willing to stick our heads up when the bullets are flying and endure protracted battles with editors and

reviewers. Publishing in journals in this "climate" takes its toll, and most folks with an objective side just give up. We would love to cite other authors who do these NCA5-type analyses using the proper methods ... there just aren't many out there. As you know, there's no profit (or funding) in fighting the climate establishment. However, please, let us know if you see something we've missed.

John C.

On Fri, Jul 11, 2025 at 11:21 AM Judith Curry <curry.judith@gmail.com> wrote:

> Re 1.4 and TX, i suggest we incorporate these points briefly in existing chapters. The content of 1.4 is already covered in CWG, apart from the convoluted peer review issue. CWG adequately covers temperature extremes, we don't need more of that in NCA beyond length of temperature records. Re TX, might fit best in CWG attribution, but its too early for that I think.
>
> In 8.3 Recommendations for NCA5, we should recommend an increased focus on predicting individual extreme events and communicating the forecast, rather than attributing them to whatever.
>
> What i'm struggling with in the NCA5 critique is that if you read it without an author list, you would figure the authors are christy, mckitrick, koonin. This should be a relatively short, high-level critique and IMO we need to depersonalize this
>
> On Fri, Jul 11, 2025 at 8:19 AM Ross McKitrick <ross.mckitrick@gmail.com> wrote:
>
> > We seem to have stalled on iterating the NCA5 report. Here are the issues on the table:
> >
> > 1. Whether to drop Section 1.4
> >
> > - my thinking is I like the idea of the section because it justifies why we would presume to critique a report that has already gone through 11 government agencies and a National Academies review. At the

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same time I think it could be shortened and made more effective with a different version of the Figure from CWG25. John if you can you send me the spreadsheet you used I'll propose a rewrite.

2. Do we include a case study of the Texas floods?

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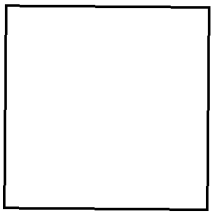

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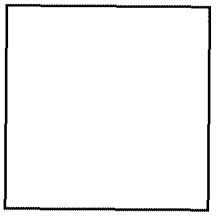

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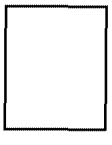

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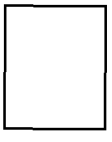

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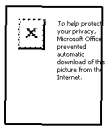

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Sent: 7/18/2025 3:46:35 PM
To: John Christy [climateman60@gmail.com]
Subject: Re: NCA5 progress

Good content... but I'm dizzy from the flashy roaming map feature. A little too much for my tastes. -Roy

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I must be missing something. Our papers directly address the issues espoused by NCA5. We offer all the data and methods. Why should our work be suppressed?

John C.

Sent from my iPhone

On Jul 11, 2025, at 1:16 PM, judith curry <curry.judith@gmail.com> wrote:

We need to think about our audience who we want to reach and influence. We don't want this to be another salvo in the climate wars. But to rise above it and be hyper objective.

Sent from my iPhone

On Jul 11, 2025, at 10:07 AM, John Christy <climateman60@gmail.com> wrote:

Judy

... Christy, McKitrick and Koonin ... you could look at it this way: we're the only ones willing to stick our heads up when the bullets are flying and endure protracted battles with editors and reviewers. Publishing in journals in this "climate" takes its toll, and most folks with an objective side just give up. We would love to cite other authors who do these NCA5-type analyses using the proper methods ... there just aren't many out there. As you know, there's no profit (or funding) in fighting the climate establishment. However, please, let us know if you see something we've missed.

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On Fri, Jul 11, 2025 at 11:21 AM Judith Curry <curry.judith@gmail.com> wrote:

> Re 1.4 and TX, i suggest we incorporate these points briefly in existing chapters. The content of 1.4 is already covered in CWG, apart from the convoluted peer review issue. CWG adequately covers temperature extremes, we don't need more of that in NCA beyond length of temperature records. Re TX, might fit best in CWG attribution, but its too early for that I think.
>
> In 8.3 Recommendations for NCA5, we should recommend an increased focus on predicting individual extreme events and communicating the forecast, rather than attributing them to whatever.
>
> What i'm struggling with in the NCA5 critique is that if you read it without an author list, you would figure the authors are christy, mckitrick, koonin. This should be a relatively short, high-level critique and IMO we need to depersonalize this
>
> On Fri, Jul 11, 2025 at 8:19 AM Ross McKitrick <ross.mckitrick@gmail.com> wrote:
>
> > We seem to have stalled on iterating the NCA5 report. Here are the issues on the table:
> >
> > 1. Whether to drop Section 1.4
> > - my thinking is I like the idea of the section because it justifies why we would presume to critique a report that has already gone through 11 government agencies and a National Academies review. At the same time I think it could be shortened and made more effective with a different version of the Figure from CWG25. John if you can you send me the spreadsheet you used I'll propose a rewrite.
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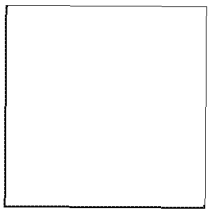

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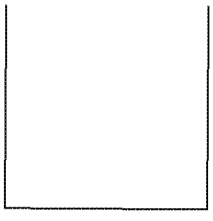

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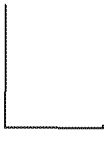

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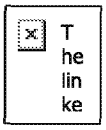

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DOJ_00000905

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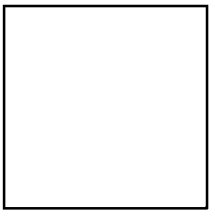

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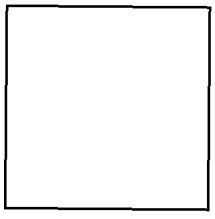

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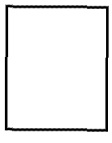

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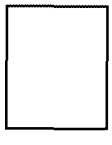

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Subject: Re: NCA5 progress
Attachments: image001.jpg

A couple of my folks did a quick write up of the TX floods.

https://www.earthdata.nasa.gov/dashboard/stories/tx-flood

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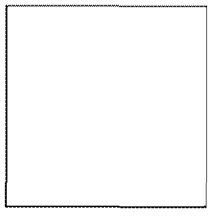

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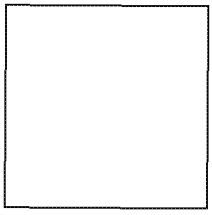

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> > ... Christy, McKitrick and Koonin ... you could look at it this way: we're the only ones willing to stick our heads up when the bullets are flying and endure protracted battles with editors and reviewers. Publishing in journals in this "climate" takes its toll, and most folks with an objective side just give up. We would love to cite other authors who do these NCA5-type analyses using the proper methods ... there just aren't many out there. As you know, there's no profit (or funding) in fighting the climate establishment. However, please, let us know if you see something we've missed.
> >
> > John C.
> >
> > On Fri, Jul 11, 2025 at 11:21 AM Judith Curry <curry.judith@gmail.com> wrote:

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On Fri, Jul 11, 2025 at 8:19 AM Ross McKitrick <ross.mckitrick@gmail.com> wrote:

> We seem to have stalled on iterating the NCA5 report. Here are the issues on the table:
>
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>
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>
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DOJ_00000923

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- I find the LLM critiques to be somewhat helpful in anticipating possible lines of attack, but they are overly algorithmic and often end up saying "they make a valid point but that's not the consensus so it's probably wrong." And it seems to have hallucinated about things we didn't even say. Still, it points to the need to guard against snark.

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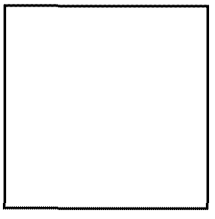

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CFAN - Climate Forecast Applications Network
Reno, NV USA
curry.judith@cfanclimate.com | +1.404.803.2012
http://www.cfanclimate.net

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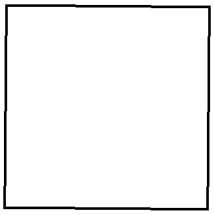

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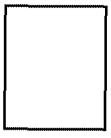

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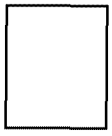

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http://www.cfanclimate.net

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Judith Curry, President
CFAN - Climate Forecast Applications Network
Reno, NV USA
curry.judith@cfanclimate.com | +1.404.803.2012
http://www.cfanclimate.net

From: Roy Spencer [roywspencer@hotmail.com]
Sent: 7/18/2025 10:28:51 AM
To: Steven Koonin [steven.koonin@gmail.com]; 'Judith Curry' [curry.judith@gmail.com]; 'Ross McKitrick' [ross.mckitrick@gmail.com]
CC: 'John Christy' [climateman60@gmail.com]; 'Travis Fisher' [travis.scott.fisher@gmail.com]; 'Josh Loucks' [loucksj14@gmail.com]; 'Seth Cohen' [seth.cohen@hq.doe.gov]
Subject: Re: NCA5 progress
Attachments: NCA5.Review.July17.[RM] JC RS.docx

I've added several edits to Judy's version (attached).

-Roy

From: Steven Koonin <steven.koonin@gmail.com>
Sent: Wednesday, July 16, 2025 5:29 AM
To: 'Judith Curry' <curry.judith@gmail.com>; 'Ross McKitrick' <ross.mckitrick@gmail.com>
Cc: 'John Christy' <climateman60@gmail.com>; 'Travis Fisher' <travis.scott.fisher@gmail.com>; 'Roy W. Spencer' <roywspencer@hotmail.com>; 'Josh Loucks' <loucksj14@gmail.com>; 'Seth Cohen' <seth.cohen@hq.doe.gov>
Subject: RE: NCA5 progress

And my further edits attached.

Do keep me at least cc'd over the next few days – I'll respond as I'm able.

SEK

From: Judith Curry <curry.judith@gmail.com>
Sent: Tuesday, July 15, 2025 7:05 PM
To: Ross McKitrick <ross.mckitrick@gmail.com>
Cc: John Christy <climateman60@gmail.com>; Steven Koonin <steven.koonin@gmail.com>; Travis Fisher <travis.scott.fisher@gmail.com>; Roy W. Spencer <roywspencer@hotmail.com>; Josh Loucks <loucksj14@gmail.com>; Seth Cohen <seth.cohen@hq.doe.gov>
Subject: Re: NCA5 progress

Here is my revised version. One proposed change of substance, relates to TX floods.

In section 8.3, i proposed modifying one of the bullets:

- The range of climatic and weather conditions, including extremes, that have occurred in the past and can reasonably be expected to occur in U.S. regions over the near future. An example of a salient acute failure is the NCA5 chapter (region that includesTexas) that fails to mention the historical occurrence and future risk of flash floods in the Texas Hill Country ROSS MAYBE MENTION WHAT NCA5 SAID ABOUT TX FLOODS in REGIONAL CHAPTER, THEN INCLUDE LINK TO YOUR MINI ANALYSIS

An alternative approach would be to add a new chapter on Failure to document the risk of extreme events based on the historical data base, something like that. Simpler just to mention it in Section 8.3

On Tue, Jul 15, 2025 at 3:33 PM Ross McKitrick <ross.mckitrick@gmail.com> wrote:

If Steve's away until Tuesday a Friday July 18 deadline won't be feasible, so let's work towards a Friday July 25 deadline.

I propose this week we go in the following order to prevent us working on overlapping drafts
Judy goes through the draft tonight
Steve has another look tomorrow.
Then Roy, then John, then me.

On Tue, Jul 15, 2025 at 3:47 PM John Christy <climateman60@gmail.com> wrote:

I like Judy's idea. It's one way to avoid going through the preparation and experience of something like a colonoscopy twice in one month.

John C.

On Tue, Jul 15, 2025 at 2:12 PM Judith Curry <curry.judith@gmail.com> wrote:

Here is a way around the NCA4 issue, propose adding the following text to end of section 8.3

NCA4 provided a better assessment than NCA5 in terms of a more thorough consideration climate science, use of data back to 1901, and less of an advocacy tone. However, NCA4 shared the following endemic problems with NCA5

- Overconfidence in conclusions
- Inadequate treatment of natural variability
- Inadequate Traceable Accounts and communication of uncertainty
- Over reliance on extreme scenarios

On Tue, Jul 15, 2025 at 12:02 PM Steven Koonin <steven.koonin@gmail.com> wrote:

Just a heads up that I will be on the West Coast with very limited connectivity from tomorrow (Wednesday) evening through Monday evening (West Coast times). Back on the East Coast early Tuesday morning.

SEK

From: Travis Fisher <travis.scott.fisher@gmail.com>
Sent: Tuesday, July 15, 2025 1:47 PM
To: Steven Koonin <steven.koonin@gmail.com>
Cc: Judith Curry <curry.judith@gmail.com>; Ross McKitrick <ross.mckitrick@gmail.com>; John Christy <climateman60@gmail.com>; Roy W. Spencer <roywspencer@hotmail.com>; Josh Loucks <loucksj14@gmail.com>; Seth Cohen <seth.cohen@hq.doe.gov>
Subject: Re: NCA5 progress

Hi all,

If we need to move quickly to publish the NCA critique as a DOE product, what would be a reasonable date for us to consider it final from the authors' point of view (subject to internal review for errors but not subject to political meddling)? I have to build a publication schedule, and I'd like to work backward from a date that's comfortable for you all.

I ask because the political powers that be are interested in having a published version to cite. Sooner is better, of course, but I don't want to jam you up. They certainly want it to be published before we could conceivably have a new head of the USGCRP, so it will have to be a DOE report.

Finally, if you're considering critiquing the entire NCA apparatus and previous reports, I think that would be helpful. The political response to an NCA5 critique so far has been (I'm paraphrasing), "Even if we show that NCA5 is not a solid basis for policymaking, what about NCA4 and prior reports?"

As always, please feel free to call me or convene a meeting if you want to discuss anything. I'll also try to keep everyone posted as the CWG report moves through the necessary hoops.

Best,
Travis

On Tue, Jul 15, 2025 at 11:41 AM Steven Koonin <steven.koonin@gmail.com> wrote:

> I've marked up Judy's "desnarked" version (attached). Mostly typos and wording, but a few issues of substance. And still on the fence about whether and how to include the NCA4 story on temperature extremes.
>
> SEK
>
> ---
>
> **From:** Judith Curry <curry.judith@gmail.com>
> **Sent:** Sunday, July 13, 2025 3:12 PM
> **To:** Ross McKitrick <ross.mckitrick@gmail.com>
> **Cc:** Steven Koonin <steven.koonin@gmail.com>; John Christy <climateman60@gmail.com>; Roy W. Spencer <roywspencer@hotmail.com>; Travis Fisher <travis.scott.fisher@gmail.com>; Josh Loucks <loucksj14@gmail.com>; Seth Cohen <seth.cohen@hq.doe.gov>
> **Subject:** Re: NCA5 progress
>
> see attached for a shorter, desnarked version of NCA5 for you to consider. I didn't do track changes, its clean text
>
> On Sun, Jul 13, 2025 at 10:55 AM Ross McKitrick <ross.mckitrick@gmail.com> wrote:
>
> > Steve- this is the most recent version I have. There is also a Supplement on precip trends.
> >
> > On Sat, Jul 12, 2025 at 6:18 PM Steven Koonin <steven.koonin@gmail.com> wrote:
> >
> > > Ross- Can you send around the most recent version of the NCA5 review. I can't seem to identify it in the emails and would like to go through it again in the next few days.
> > >
> > > SEK
> > >
> > > ---
> > >
> > > **From:** Ross McKitrick <ross.mckitrick@gmail.com>
> > > **Sent:** Friday, July 11, 2025 3:49 PM
> > > **To:** John Christy <climateman60@gmail.com>
> > > **Cc:** judith curry <curry.judith@gmail.com>; Roy W. Spencer <roywspencer@hotmail.com>; Steven Koonin <steven.koonin@gmail.com>; Travis Fisher <travis.scott.fisher@gmail.com>; Josh Loucks <loucksj14@gmail.com>; Seth Cohen <seth.cohen@hq.doe.gov>
> > > **Subject:** Re: NCA5 progress
> > >
> > > John and I only appear in Section 4.1 as part of challenging the reproducibility of the NCA5 Key Message regarding precipitation. 2 of our 3 citations in the reference list are data archives which are there for transparency purposes.

On Fri, Jul 11, 2025 at 2:53 PM John Christy <climateman60@gmail.com> wrote:

Judy

I must be missing something. Our papers directly address the issues espoused by NCA5. We offer all the data and methods. Why should our work be suppressed?

John C.

Sent from my iPhone

On Jul 11, 2025, at 1:16 PM, judith curry <curry.judith@gmail.com> wrote:

We need to think about our audience who we want to reach and influence. We don't want this to be another salvo in the climate wars. But to rise above it and be hyper objective.

Sent from my iPhone

On Jul 11, 2025, at 10:07 AM, John Christy <climateman60@gmail.com> wrote:

Judy

... Christy, McKitrick and Koonin ... you could look at it this way: we're the only ones willing to stick our heads up when the bullets are flying and endure protracted battles with editors and reviewers. Publishing in journals in this "climate" takes its toll, and most folks with an objective side just give up. We would love to cite other authors who do these NCA5-type analyses using the proper methods ... there just aren't many out there. As you know, there's no profit (or funding) in fighting the climate establishment. However, please, let us know if you see something we've missed.

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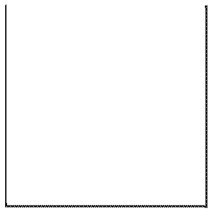

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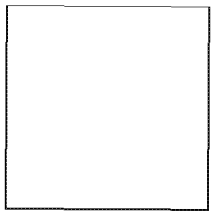

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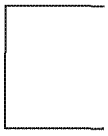

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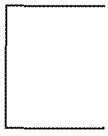

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Critique of the Fifth National Climate Assessment

EXECUTIVE SUMMARY 3

1 INTRODUCTION 4

1.1 About this Report 4
1.2 About the National Climate Assessments 4
1.3 Standards for Assessing NCA Products 5

2 NCA5 OVERVIEW CHAPTER: ADVOCACY LANGUAGE AND UNSCIENTIFIC TONE 6

3 OVERCONFIDENCE WHEN STATING CONCLUSIONS 7

3.1 Inflated certainty levels 7
3.2 Overstating findings in underlying sources 9
3.3 Example: Emergent constraints 9

4 ARBITRARY AND AMBIGUOUS TREND ANALYSES 10

4.1 Average and Extreme Precipitation 11
4.2 Heatwaves 11

5 INADEQUATE TRACEABLE ACCOUNTS 14

6 OVEREMPHASIS ON EXTREME SCENARIOS 16

7 CONFLATION OF NATURAL AND ANTHROPOGENIC CLIMATE CHANGES 18

8 SUMMARY EVALUATION OF NCA5 AND RECOMMENDATIONS FOR NCA6 19

8.1 Compliance with USGCRP's statutory obligation 19
8.2 Adherence to the tenets of Gold Standard Science 20
8.3 Suitability for informing Federal climate and energy policy 20
8.4 NCA5 and the 2025 Texas Floods 22
8.5 Recommendations for NCA6 24

9 REFERENCES 25

10 APPENDIX: CHARGE TO THE REVIEW 27

ABOUT THE AUTHORS 28

DOJ_00000933

EXECUTIVE SUMMARY

This report critically evaluates the Fifth National Climate Assessment (NCA5), finding it an inadequate basis for climate and energy policies. A detailed review of the foundational chapters on climate science raises several key concerns:

Scientific Integrity

- An advocacy tone, particularly in the Overview chapter, that is inconsistent with scientific objectivity
- Endemic overconfidence when stating conclusions, including inflated certainty levels and overstatement of findings from underlying sources
- No mentions of dissent, disagreement or controversies
- Policy prescriptions that ignore costs and tradeoffs

Flawed methodology

- Minimal discussion of observational inadequacies
- Use of short time periods for trend analyses; lack of a consistent rationale for choosing time scales
- Attribution is implied, not dissected
- Overemphasis on extreme scenarios for future emissions and sea level rise
- Inadequate traceable accounts to support key conclusions

Inadequate Review Process

- A review by the National Academy of Sciences, Engineering, and Medicine (NASEM) failed to identify some fundamental flaws in NCA5
- The NCA5 authors failed to adopt some improvements recommended by NASEM

The report shows NCA5 to be a biased and incomplete picture of climate science that skews toward excessive climate risk. Consequently, NCA5 should not be used as a basis for climate and energy policies.

DOJ_00000934

1 INTRODUCTION

1.1 About this Report

This report responds to a request from the Office of Science and Technology Policy (OSTP) Director Michael Kratsios (reproduced in the Appendix) [MAY HAVE TO MODIFY THIS] that we assess the suitability of the Fifth National Climate Assessment (NCA5 2023) for informing climate and energy policies.

To conduct this assessment, we reviewed NCA5 itself, the National Academies of Science, Engineering and Medicine (NASEM) review of the Third Order NCA5 Draft, and the USGCRP responses to that review. We have drawn upon our long experience working on advisory reports, including for the NASEM, the Intergovernmental Panel on Climate Change (IPCC), and other organizations as writers, reviewers, and study leaders. We have reviewed recent scientific developments in a separate report to Energy Secretary Wright (Climate Working Group 2025) herein denoted "CWG25".

We find that NCA5 should not be relied on for policy making as it portrays an incomplete and misleading picture of current climate variability and how climate-related risks are or are not changing over time. NCA5 was selective and incomplete in its survey of climate science. The overall effect of its biases and omissions is an unfocused and excessively dire picture of climate risk.

To support our finding, the following sections of this chapter provide some background on the National Climate Assessments and the standards by which we have assessed NCA5. Chapters 2 through 7 detail important ways in which NCA5 fails to meet those standards. Finally, Chapter 8 summarizes our evaluation of NCA5 and makes recommendations for NCA6.

1.2 About the National Climate Assessments

The U.S. Global Change Research Program (USGCRP) was established by Presidential Initiative in 1989 and mandated by Congress in the Global Change Research Act (GCRA) of 1990 to develop and coordinate "a comprehensive and integrated United States research program which will assist the Nation and the world to understand, assess, predict, and respond to human-induced and natural processes of global change."

The National Climate Assessment (NCA) Reports evolved from the GCRA requirement to:

> Prepare and submit to the President and the Congress an assessment which (1) integrates, evaluates, and interprets the findings of the Program and discusses the scientific uncertainties associated with such findings; (2) analyzes the effects of global change on the natural environment, agriculture, energy production and use, land and water resources, transportation, human health and welfare, human social systems, and biological diversity; and (3) analyzes current trends in global change, both human-induced and natural, and projects major trends for the subsequent 25 to 100 years.

The five NCA Reports to date have interpreted this mandate in different ways:

- NCA1 (2000) was a multidisciplinary effort to study and portray in regional detail the potential effects of human-induced global warming on the United States.

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- NCA2 (2009) was a relatively short report that not only focused on the potential consequences of climate change but also sought to identify potential adaptation measures and identify the highest priorities for future research.
- NCA3 (2014) was an expanded effort that continued along the lines of NCA2, and was distinguished by a comprehensive review process, including a review by the National Academy of Sciences. NCA3 introduced a traceability analysis for each key finding, including a description of uncertainties.
- NCA4 (2017/2018) was a further expanded effort that was published in two volumes: I Climate Science Special Report (CSSR), and II Impacts, Risk, and Adaptation in the United States. This was the first NCA report to devote significant effort to assessing climate science.
- NCA5 (2023) returned to a single volume format, reducing discussion of climate science to a cursory two chapters, with continuing focus on regional and sectoral impacts of climate change. NCA5 expanded its remit to topics that are arguably outside the purview of the USGCRP, focusing on "Climate Action" and policy recommendations with a social justice emphasis.

These successive interpretations of the NCA are poorly aligned with the GCRA's statutory requirements. Only NCA4 gives serious consideration to climate science, which receives the great majority of USGCRP funding, and even then NCA4 misrepresents some important points. Natural climate variability is essentially dismissed as unimportant in NCA4 and barely mentioned in NCA5 in most contexts, despite the mandate to include both human-caused and natural climate change. Most significantly, NCA5 has redirected the focus away from climate science and even the hazard elements of impacts, towards evaluation of societal vulnerabilities and advocacy for particular policy options, especially deployment of wind and solar power generation.

1.3 Standards for Assessing NCA Products

Beyond the statutory requirements stated above, another pertinent standard is President Trump's executive order of May 23, 2025, Restoring Gold Standard Science. It enumerates some of the characteristics of good science, namely that it should be:

i. reproducible;
ii. transparent;
iii. communicative of error and uncertainty;
iv. collaborative and interdisciplinary;
v. skeptical of its findings and assumptions;
vi. structured for falsifiability of hypotheses;
vii. subject to unbiased peer review;
viii. accepting of negative results as positive outcomes; and
ix. without conflicts of interest.

For an assessment of policy relevant science, it is also important to include statements about the strength of knowledge. The IPCC's approach to assessing strength of knowledge is based on judgment of the available evidence and agreement among experts. But there are more sophisticated knowledge characterizations for risk management. Here are the elements according to Aven (2017):

- The degree to which the assumptions made are reasonable/realistic based on background knowledge

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- The degree to which data/information exists and are reliable and relevant
- The degree to which there is disagreement among experts (including those from different environments or academic fields)
- The degree to which the phenomena involved are understood and accurate models exist
- The degree to which the knowledge has been thoroughly examined with respect to unknown knowns (issues that are known to matter but are ignored, such as, in this context, natural variability).

2 NCA5 Overview Chapter: Advocacy language and unscientific tone

NCA5 Chapter 1, "Overview", holds a prominent place in the Report since it summarizes the entire report and is the only section that many will read. Chapter 1 is marred by an activist tone, language that aggressively promotes mitigation policies, and motivated optimism. As such, this chapter adds an imprimatur of scientific authority to naïve and simplistic declarations of opinion about public policy. Here are some examples.

Chapter 1 opens with:

> The more the planet warms, the greater the impacts. Without rapid and deep reductions in global greenhouse gas emissions from human activities, the risks of accelerating sea level rise, intensifying extreme weather, and other harmful climate impacts will continue to grow. Each additional increment of warming is expected to lead to more damage and greater economic losses compared to previous increments of warming, while the risk of catastrophic or unforeseen consequences also increases.

This statement presupposes that all warming is anthropogenic, that all warming is bad and causes economic damage, and that warming intensifies extreme weather. Such sweeping generalizations go well beyond what science has or can establish. The statement also refers to growing risks without reference to their magnitude – a small risk that increases might still be a small risk, and a large risk might be only incrementally worsened.

On the next page one finds:

> Each additional increment of warming leads to greater risks [here it lists 7 key components of society including food security and the economy] ... Without deeper cuts in global net emissions, climate risks to the US will continue to grow... Action to limit future warming and reduce risks can have near-term benefits and opportunities: low-carbon energy jobs, Improved air quality, Health benefits, Economic benefits..."

The authors write as if climate policy does not involve trade-offs and all measures to reduce future warming will be effective and beneficial. Neither the vast body of scholarship on climate science and economics nor historical experience support such simplistic claims (CWG25). Not every additional increment of warming leads to economic harms; in fact, NCA5 Chapter 19 acknowledges that there will also be benefits. Nor is climate policy guaranteed to benefit the economy; it could impose net costs. Such misleading statements are a disservice to policymakers.

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Pages 8 and 9 of the Overview promote renewable energy options by noting, correctly, that the levelized costs of wind/solar generation have fallen sharply since 2010, and so offers this rationale for pursuing deep emission reductions:

> Recent growth in the capacities of wind, solar, and battery storage technologies is supported by rapidly falling costs of zero- and low-carbon energy technologies, which can support even deeper emissions reductions. For example, wind and solar energy costs dropped 70% and 90%, respectively, over the last decade, while 80% of new generation capacity in 2020 came from renewable sources.

Yet it has long been known that intermittent renewables generation must be supplemented by dispatchable generation to meet grid reliability standards, and that doing so (*e.g.*, through natural gas, fission, or storage) significantly increases the total cost of electricity. Further, there are yet unmet synchronization challenges in electrical grids with heavy penetration of wind and solar generation. NCA5 fails to acknowledge these facts. But more importantly, we see no reason for NCA5 to be discussing renewable energy technologies and economics in the context of its mandate.

Page 17 of the Overview introduces the discussion of risks from extreme weather events by saying "Harmful impacts from more frequent and severe extremes are increasing across the country." This creates the impression that extreme weather events are worsening and that disaster losses are driven by trends in extreme weather. While the section goes on to acknowledge that some of the increase is due to increases in the exposure and value of assets at risk, it then invokes the NOAA Billion Dollar Dataset as evidence of extreme weather getting worse. Scientists have shown that this is an invalid metric (CWG25 Section 10.2) since it measures the growth of vulnerable infrastructure, not the frequency of extreme weather, and indeed NOAA has recently withdrawn the data product. Even though the dataset was still distributed by NOAA at the time of the NCA5, the report authors failed to assess it skeptically and see that it was unfit for the purpose of measuring climate trends.

Page 23 of the Overview states, in large font:

> Climate changes are making it harder to maintain safe homes and healthy families; reliable public services; a sustainable economy; thriving ecosystems, cultures, and traditions; and strong communities.

This statement cannot be evaluated on scholarly grounds and so doesn't belong in a scientific assessment report. Its prominent inclusion points not only to the willingness of NCA5 authors to promote alarm, but also the ineffectiveness of the review process in eliminating such statements.

3 OVERCONFIDENCE WHEN STATING CONCLUSIONS

3.1 Inflated certainty levels

Overconfidence in stating conclusions has been an endemic problem in NCA Reports. The authors frequently make sweeping generalizations without appropriate caveats or acknowledging uncertainties. The overconfidence begins with inflated language to describe certainty levels.

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NCA5 uses specific terms to convey information about scientific confidence associated with important findings, observations and projections. The Front Matter of NCA5 states that

> confidence in a finding is based on the type, amount, quality, strength, and consistency of evidence; the skill, range, and consistency of methods to detect, evaluate, attribute, and interpret climate trends; and the degree of agreement across scientific information sources.

Table 1 from the Front Matter provides calibrated language for confidence assessments:

Very high:	Strong evidence (established theory, multiple sources, well documented and accepted methods, etc.). High consensus
High:	Moderate evidence (several sources, some consistency, methods vary and/or documentation limited, etc.). Medium consensus
Medium:	Suggestive evidence (a few sources, limited consistency, methods emerging, etc.) Competing schools of thought.
Low:	Inconclusive evidence (limited sources, extrapolations, inconsistent findings, poor documentation and/or methods not tested, etc.). Disagreement or lack of opinions among experts.

This terminology is obviously inflated: *high confidence* with just moderate evidence and medium consensus; *medium confidence* with only suggestive evidence and competing schools of thought. This inflation in terminology leads to overconfidence in conclusions.

Even with this inflated terminology, NCA5 further inflates the confidence level of many of its conclusions to well beyond what the IPCC has concluded with more thorough justification, and by incorrectly applying its own standards. An example is the conclusion about anthropogenic influence on climate change, arguably one of the most important scientific statements of the report.

Key Message 3.1 Traceable Account states:

> There is *very high confidence* that emissions of GHGs from human activities, fossil fuel use in particular, have unequivocally caused *all* global warming observed over the industrial era.

while the corresponding statements from IPCC AR5 and AR6 are

> **AR5:** It is *extremely likely* that *more than half* of the observed increase in global average surface temperature from 1951 to 2010 was caused by the anthropogenic increase in greenhouse gas concentrations and other anthropogenic forcings together. (IPCC, 2013)

> **AR6:** The *likely* range of total human-caused global surface temperature increase from 1850–1900 to 2010–2019 is 0.8°C to 1.3°C, with a best estimate of 1.07°C. It is *likely* that well-mixed GHGs contributed a warming of 1.0°C to 2.0°C, other human drivers (principally aerosols) contributed a cooling of 0.0°C to 0.8°C, natural drivers changed global surface temperature by –0.1°C to +0.1°C, and internal variability changed it by –0.2°C to +0.2°C. It is *very likely* that well-mixed GHGs were the main driver of tropospheric warming since 1979.

The IPCC AR5 and AR6 statements provide likelihood assessments but not a confidence level. While NCA5 claims with *very high confidence* that fossil fuels have unequivocally caused *all* global warming, AR5 refers to "*more than half* of the observed warming" and AR6 provides a more nuanced statement that relates to a *likely* range of warming contributed to by human drivers.

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3.2 Overstating findings in underlying sources

Although we did not do a detailed audit of NCA5's use of source material, spot checks suggest a pattern of overstatement.

Chapter 2 page 11 reports on an increase in precipitation in some areas and attributes it to "climate change":

> Many eastern regions of the country are getting wetter (Figure 2.4). Average annual precipitation from 2002-2021 was 5%-15% higher relative to the 1901-1960 average in the central and eastern US, a trend attributable to climate change.

NCA5 attributes the claim to Knutson and Zeng (2018). But Knutson and Zeng did not say these things nor did they analyze this particular period. For 1981-2010 they cautioned that observed changes are consistent with natural variability, and they did not claim attributable trends were observed over the United States.

As another example of overstating findings, NCA5's Chapter 2 page 18 states

> There is robust evidence that human-caused warming has contributed to increases in the frequency and severity of the heaviest precipitation events across nearly 70% of the US.

This is apparently attributed to Diffenbaugh *et al.* (2018) and Kirchmeier-Young and Zhang (2020). Diffenbaugh *et al.* presented ratios of observed occurrences of extreme events to simulated occurrence rates in CMIP6 models run with only natural forcings. They report that for 79% of the U.S., extreme rainfall events are currently more frequent than in simulations, and the ratio of occurrences will rise under future warming simulations. This is not "robust" evidence of anthropogenic influence since it requires readers to assume that climate models accurately simulate regional precipitation patterns, something that the IPCC AR6 states is uncertain (AR6 WGI SPM Box SPM 1.2, SPM Section C.1.3).

Kirchmeier-Young and Zhang used three global climate models to analyze extreme 1- and 5-day events in North America. They noted large differences among the three models in their simulated precipitation changes. Attribution results for the U.S. are reported in their online Supplement (Figure S4). Across six experiments (three models and two rainfall metrics) anthropogenic influence was detected in only one case. Also both cited references began their historical observational records only in 1961. Here again this is not "robust" evidence. It is merely suggestive, particularly since other studies have found natural variability to be predominant.

3.3 Example: Emergent constraints

Some of the overconfidence expressed by NCA5 arises by omitting discussion of counterevidence in the peer reviewed literature, ignoring dissent and disagreement. An example is the topic of "emergent constraints". NCA5 Chapter 3 page 17 invokes this concept to support its claim that key uncertainties in climate model projections have been reduced:

> An approach to reduce uncertainty in climate change projections has matured over the past decade. It is known as "emergent constraints." The term refers to strong statistical

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> relationships between highly uncertain future climate parameters and observable trends or variations in the current climate, along with a physical explanation of this relationship.

Emergent constraints appeared in the climate modeling literature as an attempt to tie climate model behavior to climate observations in hopes of generating insight into real-world equilibrium climate sensitivity (ECS). Climate models exhibit a wide range of ECS values. The idea of emergent constraints is to examine whether the models with shared sensitivity values also share a common representation of some climate process (usually related to clouds) that might influence ECS. Suppose, for example, that in low-ECS models the total cloud fraction in the tropics is strongly correlated with that in the southern midlatitudes, but in high-ECS models the correlation is weak. Then researchers could examine whether the observed correlation is strong or weak and draw a conclusion about which type of model, and therefore which ECS value, is more likely.

A problem in the emergent constraint literature is that there has been a proliferation of proposed correlations with little physical basis. NCA5 alludes to this in the Traceable Accounts section (p. 3-40) but not in the main chapter text. As shown by Schlund *et al.* (2020), many emergent constraints patterned on CMIP5 models (Coupled Model Intercomparison Project Phase 5, used for the IPCC 5th Assessment Report) failed to work on CMIP6 models (used for the IPCC 6th Assessment Report). In other words, the correlations between ECS and cloud processes present in CMIP5 models were absent in CMIP6 models, indicating that they were likely spurious rather than clues to physical processes governing the climate system. As a result, emergent constraints estimated on CMIP5 models *increased* the uncertainty of ECS, rather than decreasing it as claimed by NCA5.

Yet NCA5 incorrectly described the use of emergent constraint analysis as an advance that reduced the uncertainty of ECS and climate model projections (p. 3-38):

> Emergent constraints have been widely applied to reduce the simulated spread in the climate feedbacks that shape climate sensitivity.

4 ARBITRARY AND AMBIGUOUS TREND ANALYSES

CWG25 Chapter 6 discussed the need for care in the choice of time scale when making claims about trends in extreme weather. We provided examples from analysis of river flooding, heatwaves, and extreme precipitation to show how assertions about apparent trends based on short data sets fall apart when considering longer versions of the same data sets. NCA5 uses varying time periods for trend analyses, especially in Chapter 2 (which is focused on trends), without explaining why shorter or longer intervals were chosen. For example, page 2-4 defines temperature trends over the interval since the late 1800s whereas page 3-29 presents temperature trends over 1972-2021. Page 2-11 compares rainfall over the 2002-21 versus 1901-1960 intervals, while page 2-18 uses the interval since the late 1950s to compute trends.

A further problem is that NCA5 uses the term "trend" repeatedly without indicating if it is statistically significant (*i.e.*, distinguishable from random variability); the ambiguity creates the impression all the observed changes were significant, but readers are left to speculate. All climate variables will drift up or down over any particular time interval. Identifying the change as a trend requires showing that it is statistically significant using a variance estimator suitable for the type of data being analysed. Of particular importance is choosing a method robust to the serial correlation that is frequently present in climate data. Throughout Chapters 1 to 3, references are made to "trends" without explaining how

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they were computed. The exception was on page 1-19 which refers to urban temperature trends being calculated using the Theil-Sen estimator, although that method does not seem to have been used elsewhere. The one case where reference is made to statistical significance is on Page 2-9, referring to a trend in Atmospheric Optical Depth, but there is no explanation of how significance was determined. Page 2-19 refers to regional trends in droughts being "robust" but again fails to explain how the term was defined.

4.1 Average and Extreme Precipitation

NCA5 did not continue the NCA4 precedent of using the post-1901 interval as the time scale for its precipitation discussion. Instead, it refers to changes "since the 1950s"; NCA5 Figure 2.8 suggests 1958 might be the intended start date. Under Key Message 2.2, "Extreme Events Are Becoming More Frequent and Severe", NCA5 states (p. 2-18):

> Rainfall is becoming more extreme
> Since the 1950s, there has been an upward trend in heavy precipitation across the contiguous US. This increase is driven largely by more frequent precipitation extremes, with relatively smaller changes in their intensity.

In addition to our concerns that inferences about trends are contingent on choice of time scale, if the intended meaning of this statement is that positive and significant trends are found in heavy precipitation events across CONUS, we cannot reproduce it. In CWG25 Section 6.4, in addition to referencing previous analyses in the climate literature we presented analyses of daily U.S. precipitation data for the Pacific Coast, Southeast and Northeast regions, in all cases finding both considerable regional heterogeneity and that trends in various measures of extreme precipitation detectable on one time scale are often not detected on longer or shorter time scales. Additional analysis of stations in the upper Midwest confirm this pattern.[1] Moreover the NCA5 statement was at odds with evidence in the peer-reviewed literature (discussed in CWG Section 6.4) to which authors of this report drew NCA5 authors' attention during the review process.

The following is a more accurate summary of what U.S. precipitation data show.

> There are regionally heterogenous changes in average and extreme precipitation. Positive trends in annual average rainfall and extreme events (defined either as the annual maximum or the number of exceedances of the 99th percentile value) are generally weak or non-existent when looking at samples exceeding 130 years in length. Significant trends can be found when beginning the sample in the 1950s although in most cases the trends weaken and become insignificant when looking at the post-1980 interval. This argues against attribution of changes in precipitation to anthropogenic warming, which becomes the strongest post-1980.

4.2 Heatwaves

In contrast to NCA5, NCA4 examined heat extremes across the entire 20th century, pointing out that peak heat wave activity was reached in the 1930s and has decreased since then, and that recent increases are confined to areas west of the Rockies. NCA4 stated:

[1] See details at https://www.nsstc.uah.edu/data/ushcn_jrc/SI.Precipt_trends_reproducing.pdf, which provides access to data and code.

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[The] warmest daily temperature of the year increased in some parts of the West over the past century, but there were decreases in almost all locations east of the Rocky Mountains. In fact, all eastern regions experienced a net decrease, most notably the Midwest (about 2.2°F [1.2°C]) and the Southeast (roughly 1.5°F [0.8°C]).

Since the mid-1960s, there has been only a very slight increase in the warmest daily temperature of the year (amidst large interannual variability). Heat waves (6-day periods with a maximum temperature above the 90th percentile for 1961–1990) increased in frequency until the mid-1930s, became considerably less common through the mid-1960s, and increased in frequency again thereafter. As with warm daily temperatures, heat wave magnitude reached a maximum in the 1930s.
(NCA4 pp. 190-191)

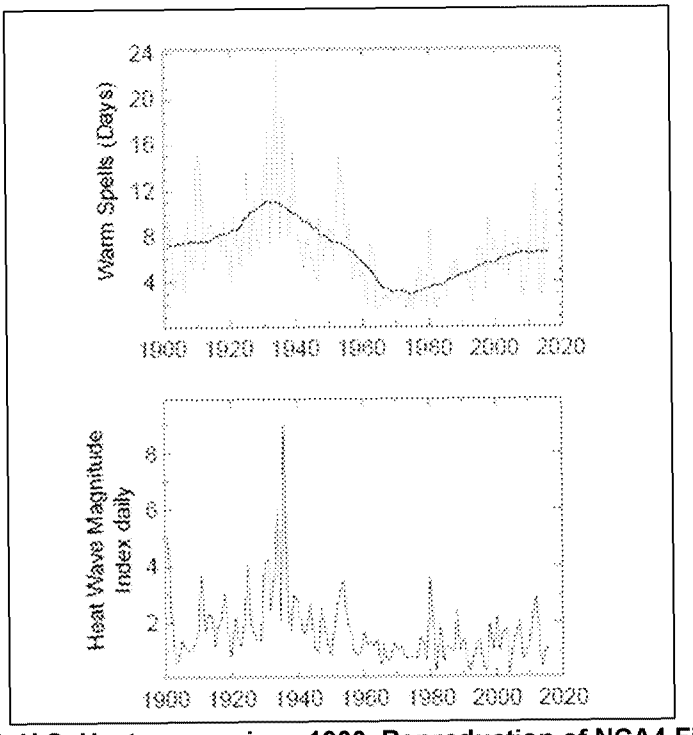

FIGURE 3. U.S. Heat waves since 1900. Reproduction of NCA4 Figure 6.4

Contrast this careful and factual language with? NCA4 with NCA5 Key Message 2.2: "Extreme Events Are Becoming More Frequent and Severe." This blanket statement is followed by NCA5 Figure 2.7 (reproduced as Figure 4 below) which shows the number of hot days, cold days and warm nights (respectively in panels a—c) over the period 2002-2021 compared to 1901-1960. Presumably these are annual counts, although this is not stated in the caption.

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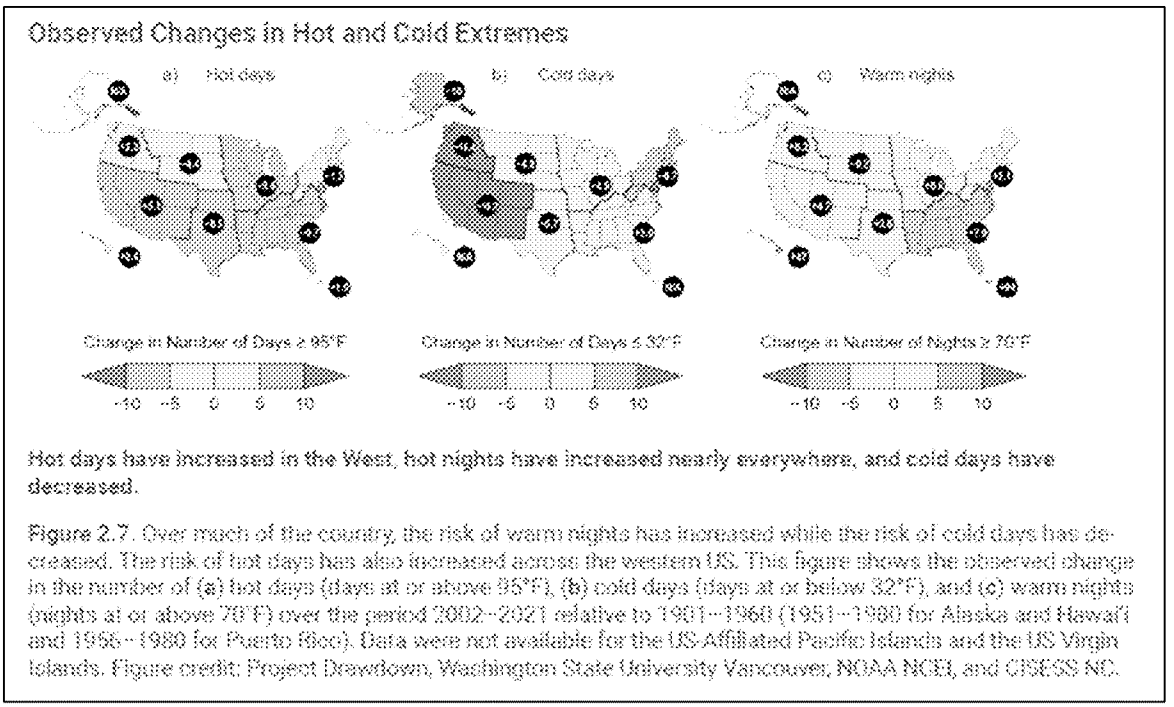

FIGURE 4: Reproduction of NCA5 Figure 2.7.

Close inspection shows that this figure actually contradicts the NCA5 Key Message with respect to heatwaves and instead reinforces the position of NCA4. Notwithstanding Key Message 2.2, the leftmost panel in NCA5 Figure 2.7 above shows that over most of CONUS the number of extreme heat days has *decreased* in recent decades compared to the prior century.

The accompanying discussion in NCA5 becomes convoluted as it appears to be aimed at supporting the Key Message despite the contrary evidence. NCA5 Chapter 2 elaborates on Key Message 2.2 by stating (page 2-16):

> Observations show an increase in the severity, extent, and/or frequency of multiple types of extreme events. Heatwaves have become more common and severe in the West since the 1980s (*high confidence*).

But while it mentions the increase in hot days in the West, it fails to mention the decrease everywhere east of the Rockies. On the next page (page 2-17) it raises the comparison to the 1930s and then switches to discussing global counts:

> By some measures, the most extreme heatwaves on record in the United States occurred during the Dust Bowl era of the 1930s. ... Globally such heatwaves are becoming more frequent, and in recent decades the western United States has been following those trends.

The reference to a global trend seems to be an attempt to tie heatwaves to anthropogenic climate change. But the obvious question, unaddressed by NCA5, is why one region follows the global pattern of increasing heatwaves while most of the country is trending in the opposite direction. These issues are addressed in Chapter 6 of CWG25, demonstrating that the range and magnitude of extreme temperatures are driven more by natural variability than by anthropogenic forcing. The analysis in CWG25 shows that for both (a) hot days (≥ 95°F) and (b) number of days in heatwaves, the current decade is no hotter than a century ago in the U.S. Thus, the NCA5 claim that "multiday heatwaves

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have become hotter, more frequent, larger, and longer lasting in recent decades," is simply false when expanding the temporal and spatial domains to encompass all available data (Chapter 6 and Figure 6.3.6 of CWG25).

NCA5 then pointed to the dramatic Pacific Northwest heatwave of 2021. CWG25 Section 8.6.1 discusses this event in detail, reviewing the multiple peer reviewed studies that explained the unusual meteorological context was unrelated to human-caused climate change, a point omitted from the NCA5 discussion.

NCA5 finally addresses the declining heatwave trend in CONUS east of the Rockies but attempts to reframe it by focusing on urban warm spells.

> [The] number of very hot days has actually decreased across the central and eastern regions due to summer cooling trends in the region (Figure 2.7; Ch. 22). This does not, however, mean the central and eastern US are not affected by heat. The impacts of extreme high temperatures are more severe if such conditions persist for several days, and overall, multiday heatwaves have become hotter, more frequent, larger, and longer lasting in recent decades. Across 50 large US cities, the US Global Change Research Program heatwave indicator (https://www.globalchange.gov/indicators/heat-waves) shows that the average number of heatwaves has doubled since the 1980s, and the length of the heatwave season has increased from about 40 days to about 70 days.

We discussed this part of NCA5 in CWG25 Section 6.3. The figure referenced by NCA5 uses a short time period which begins in the 1960s, the coldest decade in the last 100 years, thus suppressing any comparison to the 1930s. Further, nighttime temperatures in urban areas have increased faster than daytime temperatures (which NCA5 acknowledges), but this is a signature of urban heat islands and is not a good metric of climate change. CWG25 found that the occurrence of hot days (≥ 95° F) has recently increased in the West but declined since 1899 in the remainder of the country and in the nationwide average.

5 INADEQUATE TRACEABLE ACCOUNTS

NCA3 began the practice of including a section on Traceable Accounts at the end of each chapter. This is the description from NCA5:

> Each chapter concludes with a section entitled Traceable Accounts, which provides information on the overall process used to develop the chapter as well as a separate Traceable Account section for each Key Message. These Traceable Accounts describe the supporting evidence behind each Key Message, the process and rationale authors used in reaching their conclusions, and the author team's expert assessment of the confidence in and, where applicable, likelihood of these conclusions. As such, Traceable Accounts provide information about the state of the science, document sources of uncertainty, identify research gaps, and allow traceability to data and resources.

The Traceable Accounts for each Key Message includes the following sections:

- Description of Evidence Base
- Major Uncertainties and Research Gaps

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- Description of Confidence and Likelihood

The Traceable Accounts could have addressed the statutory requirement that the NCA discuss scientific uncertainties. They could also help satisfy the Executive Order for Restoring Gold Standard Science by addressing reproducibility, transparency, communication of error and uncertainty, and skepticism of findings and assumptions. However, the Traceable Accounts in NCA5's Chapters 2 and 3 are uneven, often superficial and uninformative.

An example of a deficient Traceable Account is NCA5's Key Message 2.2: "Extreme Events are Becoming More Frequent and Severe". The "Description of the Evidence Base" offers two paragraphs, the first summarizing the findings and the second generically describing the types of data that can be used for storms. "Major Uncertainties and Research Gaps" focuses on the uneven distribution across U.S. populations due to differences in exposure and vulnerability. The only limitations in data referred to are the lack of a long-term record of lightning and the lack of homogenized daily and hourly temperature data apart from reanalysis products.

But the most astonishing deficiency is in the "Description of Confidence and Likelihood." One of the statements in Key Message 2.2 is:

> Hurricanes have been intensifying more rapidly since the 1980s (*high confidence*) and causing heavier rainfall and higher storm surges (*high confidence*).

The Description of Confidence and Likelihood includes the following statement:

> Basic physical understanding and climate models both provide robust explanations for the links between climate change and observed changes in these extremes: this is why the authors also have high confidence that storms are delivering more rainfall and high confidence that storm surges are becoming higher.

No reference to journal publications or a specific data set is made anywhere in the chapter regarding hurricane-induced precipitation or storm surge to support this *high confidence* conclusion.

The Traceable Accounts for the various Key Findings of Chapter 3 have some substantial inconsistencies. Consider

> Key Message 3-1: Human activities have caused global warming.
> Confidence and Likelihood: "There is *very high confidence* that emissions of GHGs from human activities, fossil fuel use in particular, have *unequivocally* caused all global warming observed over the industrial era. There is also *very high confidence* that changes in natural climate drivers have had globally small and regionally variable long-term effects over this period."

The Uncertainties section addresses only uncertainties in radiative forcing by greenhouse gases, ignoring the great uncertainty in model responses to that forcing (CWG25 Chapters 4 and 5) In contrast, the Traceability Analysis of Key Message 3-4 ("Humans Are Changing Earth System Processes") raises the problem that relatively little is known about the role of natural variability at the regional scale. From its Description of Evidence Base:

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> In the last decade, there has been increasing recognition of the role of regional-scale natural variability in the past and future evolution of climate, as well as the fact that regional natural variability signals can be competitive with forced anthropogenic signals.

And from its Major Uncertainties and Research Gaps:

> For example, the true natural variability of the climate system on decadal to centennial timescales could be larger than what we estimate from GCMs, which would further increase the irreducible uncertainty stemming from natural variability.

These statements are among the most scientifically credible in the entire NCA5 and they directly undercut the confidence assigned to Key Message 3-1.

There is also a generic problem in tracing NCA5's Traceable Accounts. The Front Matter of NCA5 states:

> Each figure and some tables are accompanied by a metadata survey, which can be accessed in the online version of the report by clicking on the eyeball icon above the figure or table (see the table below for explanations of additional icons used throughout the report). The metadata survey describes data sources, figure or table development methods, copyright information, and other important documentation.

Clicking on the 'eyeball' icon does not reveal the metadata information; instead a "Contact Us" email appears, addressed to the USGCRP. This is an inadequate way to archive the metadata information.

In summary, the Traceable Analyses examined here, with few exceptions, fail to meet the stated objectives of the NCA.

6 Overemphasis on Extreme Scenarios

To respond to the GCRA mandate to "project major trends for the subsequent 25 to 100 years," NCA5 relies on projections of future climate change based on estimates of future emissions (the so-called SSP scenarios) and/or specified levels of radiative forcing (the RCP scenarios). For the most part, NCA5 uses scenarios developed for the IPCC Assessment Reports.

CWG25 Section 3.2.1 presented a critical assessment of past and current IPCC scenario envelopes, showing that they have tended to overshoot observed emissions. IPCC AR6 published in 2021 stated that "The likelihood of high-emission scenarios like RCP8.5 and SSP5-8.5 is considered low in light of recent energy sector developments." and that same year UN Climate Negotiators (COP) stopped using scenarios above 4.5.

NCA5 makes the following observations about the scenarios they use:

> NCA5 authors were advised to assess the full range of scenarios available. (Front Matter)

> Scenarios of future emissions and land-use change are developed as plausible alternatives, but no relative likelihood is attached to them. Some recent studies, however, have argued that

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the highest scenario, SSP5-8.5, is no longer plausible without a reversal of current trends in the adoption of renewables and energy efficiency. (Key Message 3.3 Traceable Analysis)

Despite acknowledging the issue, NCA5 otherwise ignored the problem. A keyword search of mentions of NCA5 RCP/SSP scenarios finds over 50% referred to the extreme emissions scenarios RCP8.5/SSP5-8.5. Further, nine NCA5 figures (5.2, 6.9, 7.4, 11.3, 14.6, 22.13, 22.19, 27.9, 29.13) included *only* the 8.5 scenarios.

The problem of relying on extreme scenarios is particularly acute for NCA5's sea level rise projections. The sea level rise scenarios used in NCA5 do not relate directly to the SSP emissions scenarios, but rather to specified amounts of sea level rise by 2100. Table 4 of NCA5's "Guide to Using this Report" reproduced below shows that Low relates to 0.3 m (0.98 feet), Intermediate-Low relates to 0.5 m (1.64 feet), Intermediate relates to 1.0 m (3.28 feet), Intermediate-High relates to 1.5 m (4.92 feet), and High relates to 2.0 m (6.56 feet).

Table 4. Descriptive Terms for Common Sea Level Rise Scenarios Used in NCA5

Future global mean sea level rise and sea level rise along United States coastline are shown for five scenarios in feet (and meters), relative to a 2000 baseline. The US values shown in the right half of the table are averaged across the US coastal regions, including the contiguous US, Alaska, Hawai'i and the US-Affiliated Pacific Islands, and the US Caribbean. The national values shown in the table differ substantially from regional values. For example, sea level rise is higher in the Gulf Coast and lower or even negative in some parts of Alaska. In the next 30 years (2020–2050), sea level along the contiguous US coasts is expected to rise 0.92 feet (0.28 m), the same amount of sea level rise observed over the last 100 years (1920–2020). See Chapter 9 for regional sea level information. Adapted from Sweet et al. 2022.[1]

Sea Level Rise Scenario Descriptor	Global Mean Sea Level			United States		
Year	2050	2100	2150	2050	2100	2150
Low	0.49 (0.15)	0.98 (0.3)	1.31 (0.4)	0.59 (0.18)	0.98 (0.3)	1.64 (0.5)
Intermediate-Low	0.66 (0.20)	1.64 (0.5)	2.62 (0.8)	0.75 (0.23)	1.64 (0.5)	2.95 (0.9)
Intermediate	0.92 (0.28)	3.28 (1.0)	6.23 (1.9)	0.89 (0.27)	3.28 (1.0)	6.89 (2.1)
Intermediate-High	1.21 (0.37)	4.92 (1.5)	8.86 (2.7)	1.12 (0.34)	4.92 (1.5)	8.86 (2.7)
High	1.41 (0.43)	6.56 (2.0)	12.14 (3.7)	1.38 (0.42)	6.56 (2.0)	12.46 (3.8)

TABLE 1: Reproduction of Table 4 from the Front Matter of NCA5

Considering only projections representing processes quantified with at least medium confidence, IPCC AR6 assessed global mean sea level projections for all emissions scenarios (including implausible extreme emissions scenarios) for 2100 to fall between 0.2 and 1.6 m (5th—95th percentile range). By contrast, the range of sea level rise scenarios considered by NCA5 extends to 2.0 m. Further, NCA5 fails to include plausible lower scenarios, such as 0.2 m cited by the IPCC, which also corresponds to the average rate of sea level rise over the past century.

Chapter 9 of NCA5 offers the following predictions of sea level rise:

> "Under a range of potential global warming levels, average sea level along US coastlines is *likely* to be between 12 and 20 inches above 2000 sea levels in 2050 (Figure 9.2)."

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The observed global sea level rise from 2000-2024 is only approximately 3.4 inches (0.28 feet). NCA5 is thus projecting a sea level rise during 2025 and 2050 along U.S. coasts that is 2.5 to 4.9 times the global rate observed during 2000-2024, an exceedingly implausible outcome. Chapter 9 further states:

> "There is *high confidence* and it is *likely* that sea levels will rise about 11 inches (likely range of about 9–13 inches) between 2020 and 2050"

This implies a rate of increase more than double the rate from 2000 to 2024, again an implausible outlook. In summary, NCA5 presents future sea level rise scenarios that are not directly relatable to either SSP/RCP emissions scenarios or to plausible global warming levels. The NCA5 scenarios include two that are higher than the 95th percentile for the extreme emissions scenario RCP8.5 and include hypothesized ice sheet processes in which there is low confidence. Projections to 2050 require rates of sea level rise from 2025 to 2050 that are more than double the rate observed during 2000-2024. Further, NCA5 ascribes *high confidence* to these sea level rise projections. CWG25 Section 7.3 provides further context for USGCRP projections of extraordinary sea level rise in the next 25 years.

More generally, NCA5's inclusion of, and even focus on, implausible extreme scenarios creates projections of alarming impacts that are very unlikely to be driven by anthropogenic warming.

7 Conflation of Natural and Anthropogenic Climate Changes

NCA5's Glossary defines "climate change" as a change in climate for any reason. This is technically correct, but at variance with IPCC usage, which also corresponds to the popular connotation, in which the term refers specifically to anthropogenically-caused change. The distinction is not academic- it is central both to attribution questions and to projections, since anthropogenic changes depend on emission rates, while natural changes are unavoidable. Having defined climate change broadly NCA5 then fails to distinguish natural and anthropogenic changes in context with the effect of implicitly over-attributing changes to greenhouse gas emissions.

The discussion on NCA5 page 2-4 begins "Human activities are changing the climate", then goes on to list evidence for anthropogenic GHG emissions and climate warming. The next paragraph begins "Climate change is happening now in the United States. Including Alaska, the continental US has been warming about 60% faster than the planet as a whole since 1970." The implication is that the warming of CONUS faster than the planetary average is an effect of GHG emissions. But it is an artifact of the Earth's surface being 70 percent ocean. Since the ocean warms more slowly than land, comparison of any land surface outside the tropics with the global average would show the land surface to be warming faster than the global average, regardless of the cause of the warming.

The same page goes on to say "Climate change is already affecting people in the United States. Extreme heat was estimated to be responsible for more than 700 deaths per year between 2004 and 2018 although some estimates put heat-related mortality closer to 1,300 deaths annually." But extreme heat has always occurred naturally, and whether natural or not, it has always been a risk to human health. As to trends, the data show that adaptation has caused the mortality burden of extreme heat to drop substantially in recent decades (CWG25 Section 10.3.1).

Consider also the NCA5 statement on precipitation cited in Section 3.2:

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> Many eastern regions of the country are getting wetter (Figure 2.4). Average annual precipitation from 2002-2021 was 5%-15% higher relative to the 1901-1960 average in the central and eastern US, a trend attributable to climate change.

The attribution is superfluous because the statement is a tautology by NCA5's definition of climate change. Its gratuitous inclusion effectively attributes the observed trend to greenhouse gas emissions.

Exploitation of the ambiguity inherent in the term "climate change" is endemic to NCA5. The NASEM review (pp. 23-24) flagged this problem as follows:

> The draft NCA5 report frequently describes "change" but does not consistently distinguish between natural variability and climate change. This lack of clarity can be misleading for the reader by creating the misconception that some impacts that are the result of the combination of natural variability and climate change are instead solely due to climate change... it is important for NCA5 authors to accurately identify the multiple drivers of change (including global change), in addition to climate change, and accurately attribute impacts. Clearly describing impacts due to natural variability, climate change, or a combination of the two is important not only for informing policy decisions, but also for building public understand [sic] and trust in the report's messages. Climate change and natural variability should be clearly defined in the glossary and natural variability could be introduced in chapter introductions when the concept is important for understanding key messages.

This could have been easily addressed, for example by reserving the term "climate change" for anthropogenic changes and using "climate variability" for natural changes. But the NCA5 authors seemingly ignored the recommendation.

A separate but related issue is use of the term "climate change" to refer to increases in socioeconomic vulnerabilities that have anthropogenic causes unrelated to GHGs. NCA5 page 1-19 states "Climate change exacerbates inequalities." But the issue discussed is the negative correlation between neighborhood-level income and land surface temperatures in urban areas. To the extent the correlation is real, the most likely explanation is that low-income households concentrate where housing is less expensive, which might be in neighborhoods with less nearby parkland and tree cover; that has nothing to do with CO_2 emissions.

8 Summary Evaluation of NCA5 and Recommendations for NCA6

This chapter summarizes our evaluation of NCA5 relative to OSTP's charge: whether NCA5 (1) complied with the USGCRP's statutory obligation; (2) adheres to the core tenets of Gold Standard Science; and (3) can suitably inform federal climate and energy policy. The points made in this summary analysis refer to specific sections of this report as well as to the CWG25 report.

8.1 Compliance with USGCRP's statutory obligation

As cited in Section 1.2 of this report, the Global Change Research Act requires an assessment that:

> (1) integrates, evaluates, and interprets the findings of the [Global Change Research] Program and discusses the scientific uncertainties associated with such findings;

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(2) analyzes the effects of global change on the natural environment, agriculture, energy production and use, land and water resources, transportation, human health and welfare, human social systems, and biological diversity; and
(3) analyzes current trends in global change, both human-induced and natural, and projects major trends for the subsequent 25 to 100 years.

We deem NCA5 to have fallen short when evaluated against these criteria because of the following major shortcomings (see indicated section for details):

- Inadequate assessment of the relevant topics in climate science and the hazard components of climate impacts (such as hurricanes and floods). NCA5 instead focuses on evaluation of societal vulnerabilities (such as flood infrastructure, access to air conditioning, etc.), "Climate Action," and policy recommendations with a social justice emphasis (Chapter 2).
- Overconfidence in conclusions and inadequate assessment of uncertainties (Chapter 3)
- Inadequate discrimination between natural and human-induced causes of trends and impacts (Chapter 7)
- Inadequate analysis of climate trends by relying on short time periods (Chapter 6)
- Uncritical evaluation of emission scenarios and climate model simulations in making projections for the next 25 to 100 years (Chapter 6).

8.2 Adherence to the tenets of Gold Standard Science

With respect to the tenets of Gold Standard science listed in Section 1.3 of this report, we have identified the following major shortcomings in NCA5:

- **Lack of reproducibility.** In the few examples that we examined closely, we identified an instance where we could not reproduce the findings of the NCA5, a task that should require only rudimentary data analysis (Section 4.1)
- **Lack of transparency.** In many instances, the Traceable Account fails to justify the Key Finding. Metadata was not readily accessible. (Chapter 5)
- **Inadequate communication of error and uncertainty.** The Traceable Account for each Key Message provides a section on Major Uncertainties and Research Gaps; most of the accounts that we examined were superficial and uninformative. (Chapter 5)
- **Not skeptical of findings and assumptions.** The main text of the chapters is, with few exceptions, not skeptical of its findings and assumptions and does not mention dissent or disagreement. (Chapters 3 and 5)
- **Some hypotheses and Key Messages are not falsifiable.** Key Message 13.4 is but one of many examples: "Equitable Distribution of Transportation Trade-offs and Benefits Requires Community Involvement." See discussion in Chapter 2.
- **Assumption that all changes are harmful** due to warming and additional atmospheric CO_2 (Chapter 2)
- **Inadequacy of the peer review process.** The review of the NCA5 Third Order Draft by National Academies of Science, Engineering and Medicine (NASEM) identified some of the deficiencies we have noted, but the NCA5 authors were not obligated to adopt the NASEM recommendations. More importantly, we've identified many other deficiencies in NCA5; the NASEM review did not point them out and thus lacked the rigor expected of NASEM reports.

8.3 Suitability for informing Federal climate and energy policy

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We assess that the selection and presentation of information in NCA5 makes it an unreliable basis for U.S. climate and energy policy making. For each of the elements of knowledge characterization suitable for risk management listed in Section 1.3, here are specific examples where NCA5 falls short:

- The degree to which the assumptions made are reasonable/realistic based on background knowledge
    - NCA5 focused on implausibly extreme scenarios for emissions and sea level rise and made policy recommendations without adequate consideration of the costs
- The degree to which data/information exists and are reliable and relevant
    - NCA5's unjustified assumptions about model reliability, and its use of short time periods for analysis, does not support its high-confidence conclusions
- The degree to which there is disagreement among experts, including those from different environments or academic fields
    - While NCA5 was an interdisciplinary effort, the concerns we have raised all point to a failure to canvass or communicate the full range of evidence, including data and research findings that speak against Key Messages.
- The degree to which the phenomena involved are understood and accurate models exist
    - NCA5 is not appropriately skeptical of the ability of climate models to attribute the causes of warming and extreme events or to project future climates, especially at the regional level
- The degree to which the knowledge has been thoroughly examined with respect to unknown knowns
    - A major NCA5 shortcoming is its dismissal of natural climate variability in many contexts where it should have been a major consideration

NCA5 is also problematic for informing policy because by describing everything everywhere as threatened by climate change, frequently with exaggerated language, it fails to provide guidance for policymakers who need to prioritize and allocate scarce resources for adaptation and risk management. Likewise, it advocates for ambitious mitigation policies without a proper analysis of risks and costs. The NASEM Review of the NCA5 underscores the endemic nature of this problem - their review appears to be written by authors who share many of the biases of the NCA5 team, with an inordinate focus on social and policy issues.

NCA4 was in some respects a better policy-informing assessment than NCA5. It offered a more thorough consideration of climate science, consistently used data back to 1901, and had less of an advocacy tone. But it too engaged in some misleading hyperbole, for example in its presentation of heat extremes. NCA4's Part I said (prominently and with *Very High Confidence*) on Page 19 of the Executive Summary:

> There have been marked changes in temperature extremes across the contiguous United States. The number of high temperature records set in the past two decades far exceeds the number of low temperature records.

and offered this figure in support:

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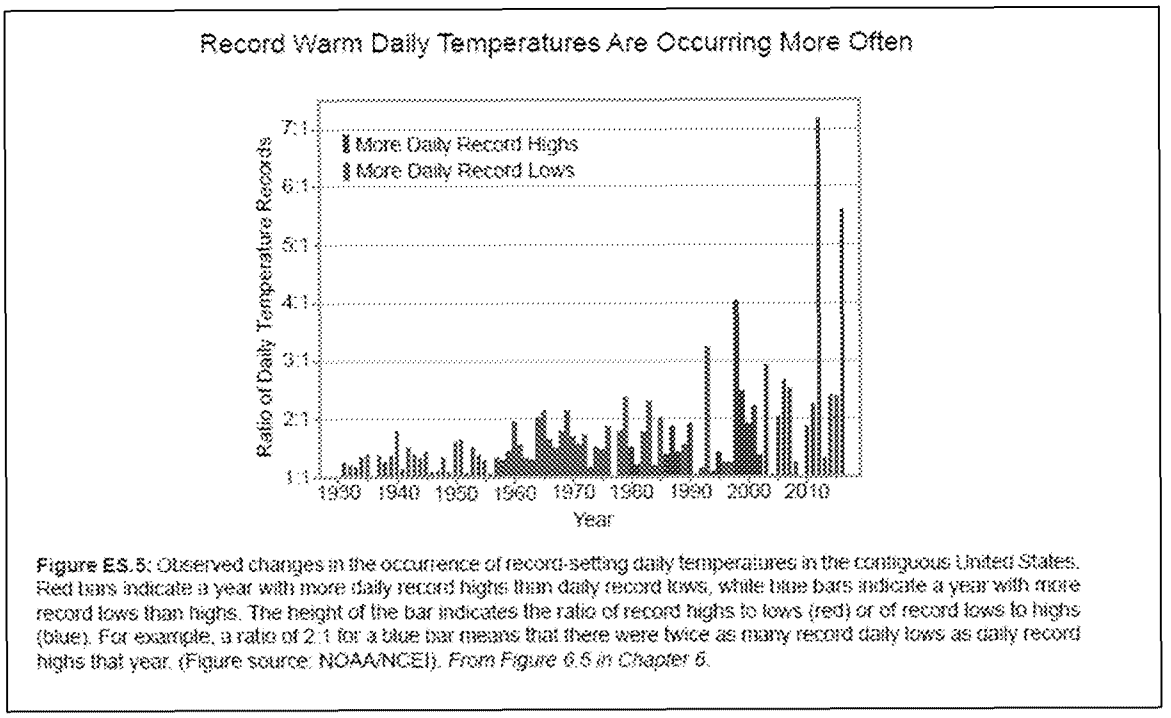

Figure ES.5: Observed changes in the occurrence of record-setting daily temperatures in the contiguous United States. Red bars indicate a year with more daily record highs than daily record lows, while blue bars indicate a year with more record lows than highs. The height of the bar indicates the ratio of record highs to lows (red) or of record lows to highs (blue). For example, a ratio of 2:1 for a blue bar means that there were twice as many record daily lows as daily record highs that year. (Figure source: NOAA/NCEI). *From Figure 6.5 in Chapter 6.*

FIGURE 5: Reproduction of Figure ES.5 from NCA4

The figure appears to show that record warm daily temperatures are occurring more often. But the underlying data (see CWG Figure 6.3.3) show the opposite: extreme heat in the U.S. peaked in the 1920s and 1930s and declined thereafter. Despite its misleading title, what Figure ES.5 shows is the *ratio* of annual warm and cold event counts. Both types of extremes declined over the sample interval, but cold events declined more than warm ones, so the ratio went up. By graphing the ratio instead of simple counts, NCA4 created a visual impression opposite to what is in the data.

NCA4 also shares with NCA5 the tendency to describe everything everywhere as under threat from climate change, undermining its usefulness for policymakers. For instance, while it contains a chapter on potential adaptation responses (Volume 2 Chapter 28) it downplays the value of such planning by stating as Key Message 2 (p. 1310) that "Climate change outpaces adaptation planning: Successful adaptation has been hindered by the assumption that climate conditions are and will be similar to those in the past."

8.4 NCA5 and the 2025 Texas Floods

To the extent an NCA should assist regional policymakers set priorities for future disaster management, we can look back at NCA4 and NCA5 and ask what relevant information they provided for the Texas Hill Country, where the tragic events of July 2025 took place. We first note that while the region in question is historically prone to flooding, the Environmental Protection Agency Climate Change Indicators record[2] shows decreasing flood frequency and magnitude since 1965 in that region; in other words the flood risk predates anthropogenic climate change and is not apparently exacerbated by it. Likewise daily precipitation records for nearby Austin are available back to 1873 and show no increase in annual average or maximum precipitation (see CWG25 Section 6.4 for links

[2] See https://www.epa.gov/climate-indicators/climate-change-indicators-river-flooding

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to data). Hence the key contribution an NCA could make is explaining the historical context of extreme rainfall events and flood risks, rather than speculations about far future changes that might occur.

The NCA4 section on the Southern great Plains states that precipitation trends are not clearly attributed to anthropogenic forcing (pp. 213-214) and that "no formal attribution of observed flooding changes to anthropogenic forcing has been claimed" (p. 241). This supports the view that the focus of resource allocation should be adapting to the known current risk profiles of the Hill Country and that there is little to be gained by trying to forecast changes under greenhouse forcing, nor would GHG emission reductions be an effective way to reduce future flood risks. However, as noted above, NCA4 undermines its own usefulness by claiming in Volume 2 Chapter 28 that climate change is happening so quickly that historical data is uninformative for planning purposes.

NCA5 presents no data on precipitation patterns in the Southern Great Plains and no information on specific high risk zones. Instead it makes sweeping unsubstantiated claims to the effect that every climate risk is getting worse over time. For example, in Chapter 26 (Southern Great Plains) the first Key Message is (p. 26-7):

> Climate change is beginning to alter how we live in the Southern Great Plains, putting us at risk from climate hazards that degrade our lands and waters, quality of life, health and well-being, and cultural interconnectedness (*high confidence*). Many climate hazards are expected to become more frequent, intense, or prolonged; to broaden in spatial extent; and to result in more people experiencing costly, deadly, or stressful climate-related conditions (*very likely, high confidence*). To address the growing risk, effective climate-resilient actions include implementing nature-based solutions; valuing Indigenous, traditional, and local knowledges; and infusing climate change solutions into community planning (*medium confidence*).

This is both inaccurate and useless for local authorities charged with setting priorities and making resource allocation decisions. The same chapter presents rainfall projections through the mid-21st century (Figure 26.10) that imply drying thoughout southern TX, but no explanation is given as to how this reconciles with projections elsewhere in NCA5 (Figure 2.12 p. 2-25) of increasing extreme precipitation in the same region. The first discussion of regional trends in heavy rainfall events is on page 26-22 which focuses entirely on sports teams having to move events indoors which results in "increasing participation costs and decreasing access to sports, especially for lower-income populations." ~~Adaptation advice consists of the following cartoon on page 26-19:~~ DELETE THIS FIGURE, DOESN"T BELONG IN CONCLUSIONS CHAPTER

DOJ_00000954

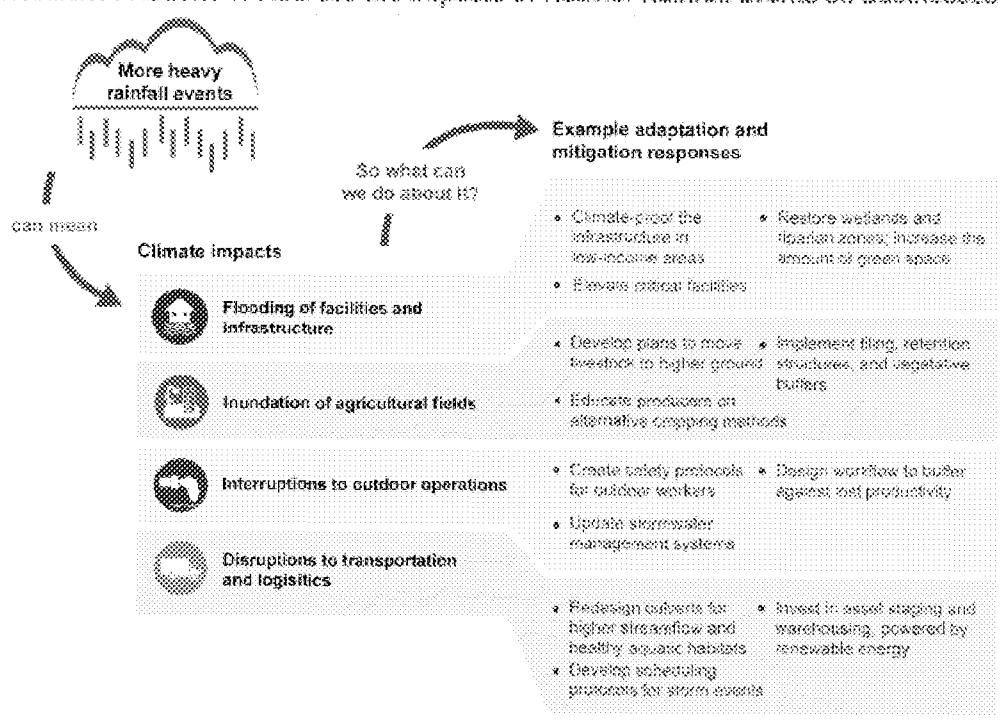

Figure 26.11. An increased number of heavy rainfall events affects business and industry across the Southern Great Plains through flooding of facilities and infrastructure, inundation of agricultural fields, interruptions to outdoor operations, and disruptions to transportation and logistics. The example adaptation and mitigation actions can increase resilience and reduce negative impacts. Figure credit: See figure metadata for contributors.

~~FIGURE 6: screenshot of NCA5 Figure 26.11~~

~~The advice is so vacuous it could have been written by someone who has never studied the topic. Combined with pervasive advocacy for renewable energy NCA5 was worse than simply unhelpful: if planners based serious decisions on it they would have misallocated resources away from potentially beneficial measures towards worthless ones.~~ A BIT SNARKY, the ABOVE TEXT SPEAKS FOR ITSELF

8.5 Recommendations for NCA6

While we have assessed NCA5 to be scientifically inadequate and unsuitable as a basis for decision-making, one can imagine a different National Climate Assessment that meets statutory and policymaker requirements. The goal should be not to persuade, but to impart understanding by being objective, transparent and complete. A suitable NCA would be an important complement to IPCC assessments to the extent that its analysis and conclusions differ where appropriate from the "consensus" of the IPCC reports and additional topics are addressed. Such a report would promote a more open scientific discussion and a more informed policy debate.

We recommend that the NCA6 have a narrower scope than NCA5, refocusing on climate science, including natural climate variability, with topics to include:

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- How the climate has varied in the past. The U.S. has the best and longest meteorological records and they should be examined and displayed in their entirety. Trend analyses should include longest periods available and employ suitable statistical methods. Local paleoclimate data should be considered where available. Analysis should demonstrate not only how the climate has varied and changed, but also regional heterogeneity. Standard, easily understandable metrics should be employed.
- The range of climatic and weather conditions, including extremes, that have occurred in the past and can reasonably be expected to occur in U.S. regions over the near future.
- A critical survey of current global and regional modeling capabilities and their suitability for regional impact assessments and projections. This would include an assessment of their ability to reproduce observed changes. It should also discuss alternative methods for generating scenario projections on regional and decadal scales, along the lines of Chapter 10 of the IPCC AR6 WGI Report.
- Assessment of the impacts of recent historical climate variability and change on ecosystems and society. Where long-term data indicate a detectable regional change, regional projections can be made for the period 2030-2050. Emissions scenarios exceeding RCP4.5/SSP2-4.5 and ECS values exceeding 4°C should not be used. Regional projections to 2100 have no credibility at this time and so should not be included in NCA6.

It is important that climate projections be assessed in context of current science capabilities. The pressures toward spatially or temporally precise projections should be resisted as the current models are not up to the task (an example is discussed in CWG25 Section 5.8). In that light, the many pages of NCA5 devoted to projected regional and sectoral impacts have little value.

Given the substantial deficiencies and biases in NCA5 that we have identified, producing an objective NCA6 report with the current NCA organizational construct would be a challenge. A NASEM review could help, but only if the selected participants reflect full viewpoint diversity and do not simply mirror the assumptions and biases of past NCA teams. We regard the CWG25 report to be a good start on NCA6 in terms of scope and objectivity, including adherence to the tenets of Gold Standard Science.

More broadly, we recommend a rewrite of the Global Change Research Act. The current mandate is vague and off point, allowing successive NCA teams to interpret the mandate as they see fit. Moreover, it is becoming increasingly clear that current and foreseeable models are not fit-for-purpose to describe regional climates, let alone usefully project them for 25 to 100 years. Further, the use of the term "global change" is ambiguous and outdated.

9 REFERENCES

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10 APPENDIX: CHARGE TO THE REVIEW

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ABOUT THE AUTHORS

[Insert updated bios]

DOJ_00000959

From: Ross McKitrick <ross.mckitrick@gmail.com>
Sent: Wednesday, July 16, 2025 4:21 PM
To: Roy Spencer
Cc: John Christy; Judith Curry; Steven Koonin; Travis Fisher; Josh Loucks; Seth Cohen
Subject: Re: NCA5 progress

Yes, then John.

On Wed, Jul 16, 2025 at 4:18 PM Roy Spencer <roywspencer@hotmail.com> wrote:

Ross, regarding your idea about us going through sequentially.. should I now go through what Steve sent? -Roy

---

From: Ross McKitrick <ross.mckitrick@gmail.com>
Sent: Tuesday, July 15, 2025 5:33 PM
To: John Christy <climateman60@gmail.com>
Cc: Judith Curry <curry.judith@gmail.com>; Steven Koonin <steven.koonin@gmail.com>; Travis Fisher <travis.scott.fisher@gmail.com>; Roy W. Spencer <roywspencer@hotmail.com>; Josh Loucks <loucksj14@gmail.com>; Seth Cohen <seth.cohen@hq.doe.gov>
Subject: Re: NCA5 progress

If Steve's away until Tuesday a Friday July 18 deadline won't be feasible, so let's work towards a Friday July 25 deadline.
I propose this week we go in the following order to prevent us working on overlapping drafts
Judy goes through the draft tonight
Steve has another look tomorrow.
Then Roy, then John, then me.

On Tue, Jul 15, 2025 at 3:47 PM John Christy <climateman60@gmail.com> wrote:

I like Judy's idea. It's one way to avoid going through the preparation and experience of something like a colonoscopy twice in one month.

John C.

On Tue, Jul 15, 2025 at 2:12 PM Judith Curry <curry.judith@gmail.com> wrote:

Here is a way around the NCA4 issue, propose adding the following text to end of section 8.3

NCA4 provided a better assessment than NCA5 in terms of a more thorough consideration climate science, use of data back to 1901, and less of an advocacy tone. However, NCA4 shared the following endemic problems with NCA5

- Overconfidence in conclusions
- Inadequate treatment of natural variability
- Inadequate Traceable Accounts and communication of uncertainty
- Over reliance on extreme scenarios

On Tue, Jul 15, 2025 at 12:02 PM Steven Koonin <steven.koonin@gmail.com> wrote:

Just a heads up that I will be on the West Coast with very limited connectivity from tomorrow (Wednesday) evening through Monday evening (West Coast times). Back on the East Coast early Tuesday morning.

SEK

From: Travis Fisher <travis.scott.fisher@gmail.com>
Sent: Tuesday, July 15, 2025 1:47 PM
To: Steven Koonin <steven.koonin@gmail.com>
Cc: Judith Curry <curry.judith@gmail.com>; Ross McKitrick <ross.mckitrick@gmail.com>; John Christy <climateman60@gmail.com>; Roy W. Spencer <roywspencer@hotmail.com>; Josh Loucks <loucksj14@gmail.com>; Seth Cohen <seth.cohen@hq.doe.gov>
Subject: Re: NCA5 progress

Hi all,

If we need to move quickly to publish the NCA critique as a DOE product, what would be a reasonable date for us to consider it final from the authors' point of view (subject to internal review for errors but not subject to political meddling)? I have to build a publication schedule, and I'd like to work backward from a date that's comfortable for you all.

I ask because the political powers that be are interested in having a published version to cite. Sooner is better, of course, but I don't want to jam you up. They certainly want it to be published before we could conceivably have a new head of the USGCRP, so it will have to be a DOE report.

Finally, if you're considering critiquing the entire NCA apparatus and previous reports, I think that would be helpful. The political response to an NCA5 critique so far has been (I'm paraphrasing), "Even if we show that NCA5 is not a solid basis for policymaking, what about NCA4 and prior reports?"

As always, please feel free to call me or convene a meeting if you want to discuss anything. I'll also try to keep everyone posted as the CWG report moves through the necessary hoops.

Best,

Travis

On Tue, Jul 15, 2025 at 11:41 AM Steven Koonin <steven.koonin@gmail.com> wrote:

> I've marked up Judy's "desnarked" version (attached). Mostly typos and wording, but a few issues of substance. And still on the fence about whether and how to include the NCA4 story on temperature extremes.
>
> SEK

From: Judith Curry <curry.judith@gmail.com>

Sent: Sunday, July 13, 2025 3:12 PM
To: Ross McKitrick <ross.mckitrick@gmail.com>
Cc: Steven Koonin <steven.koonin@gmail.com>; John Christy <climateman60@gmail.com>; Roy W. Spencer <roywspencer@hotmail.com>; Travis Fisher <travis.scott.fisher@gmail.com>; Josh Loucks <loucksj14@gmail.com>; Seth Cohen <seth.cohen@hq.doe.gov>
Subject: Re: NCA5 progress

see attached for a shorter, desnarked version of NCA5 for you to consider. I didn't do track changes, its clean text

On Sun, Jul 13, 2025 at 10:55 AM Ross McKitrick <ross.mckitrick@gmail.com> wrote:

> Steve- this is the most recent version I have. There is also a Supplement on precip trends.
>
> On Sat, Jul 12, 2025 at 6:18 PM Steven Koonin <steven.koonin@gmail.com> wrote:
>
> > Ross- Can you send around the most recent version of the NCA5 review. I can't seem to identify it in the emails and would like to go through it again in the next few days.
> >
> > SEK

From: Ross McKitrick <ross.mckitrick@gmail.com>
Sent: Friday, July 11, 2025 3:49 PM
To: John Christy <climateman60@gmail.com>
Cc: judith curry <curry.judith@gmail.com>; Roy W. Spencer <roywspencer@hotmail.com>; Steven Koonin <steven.koonin@gmail.com>; Travis Fisher <travis.scott.fisher@gmail.com>; Josh Loucks <loucksj14@gmail.com>; Seth Cohen <seth.cohen@hq.doe.gov>
Subject: Re: NCA5 progress

John and I only appear in Section 4.1 as part of challenging the reproducibility of the NCA5 Key Message regarding precipitation. 2 of our 3 citations in the reference list are data archives which are there for transparency purposes.

On Fri, Jul 11, 2025 at 2:53 PM John Christy <climateman60@gmail.com> wrote:

> Judy
>
> I must be missing something. Our papers directly address the issues espoused by NCA5. We offer all the data and methods. Why should our work be suppressed?
>
> John C.
>
> Sent from my iPhone
>
> > On Jul 11, 2025, at 1:16 PM, judith curry <curry.judith@gmail.com> wrote:
> >
> > We need to think about our audience who we want to reach and influence. We don't want this to be another salvo in the climate wars. But to rise above it and be hyper objective.
> >
> > Sent from my iPhone
> >
> > > On Jul 11, 2025, at 10:07 AM, John Christy <climateman60@gmail.com> wrote:

Judy

... Christy, McKitrick and Koonin ... you could look at it this way: we're the only ones willing to stick our heads up when the bullets are flying and endure protracted battles with editors and reviewers. Publishing in journals in this "climate" takes its toll, and most folks with an objective side just give up. We would love to cite other authors who do these NCA5-type analyses using the proper methods ... there just aren't many out there. As you know, there's no profit (or funding) in fighting the climate establishment. However, please, let us know if you see something we've missed.

John C.

On Fri, Jul 11, 2025 at 11:21 AM Judith Curry <curry.judith@gmail.com> wrote:

> Re 1.4 and TX, i suggest we incorporate these points briefly in existing chapters. The content of 1.4 is already covered in CWG, apart from the convoluted peer review issue. CWG adequately covers temperature extremes, we don't need more of that in NCA beyond length of temperature records. Re TX, might fit best in CWG attribution, but its too early for that I think.
>
> In 8.3 Recommendations for NCA5, we should recommend an increased focus on predicting individual extreme events and communicating the forecast, rather than attributing them to whatever.
>
> What i'm struggling with in the NCA5 critique is that if you read it without an author list, you would figure the authors are christy, mckitrick, koonin. This should be a relatively short, high-level critique and IMO we need to depersonalize this
>
> On Fri, Jul 11, 2025 at 8:19 AM Ross McKitrick <ross.mckitrick@gmail.com> wrote:

We seem to have stalled on iterating the NCA5 report. Here are the issues on the table:

1. Whether to drop Section 1.4

- my thinking is I like the idea of the section because it justifies why we would presume to critique a report that has already gone through 11 government agencies and a National Academies review. At the same time I think it could be shortened and made more effective with a different version of the Figure from CWG25. John if you can you send me the spreadsheet you used I'll propose a rewrite.

2. Do we include a case study of the Texas floods?

- What I like about that section is that it is a vivid example of how a document that could have provided useful info for disaster planners not only failed to do so, but it would have misdirected resources if they were to have relied on it. But it's easy to have 20/20 hindsight. Presumably somewhere in the US at this moment there are several potential weather-related hazards poised to cause death and destruction later this year, and the local authorities are not ready for them. We need to explain what it would look like for an NCA to be a useful resource in that context. What say ye all?

3. Tidying

- I find the LLM critiques to be somewhat helpful in anticipating possible lines of attack, but they are overly algorithmic and often end up saying "they make a valid point but that's not the consensus so it's probably wrong." And it seems to have hallucinated about things we didn't even say. Still, it points to the need to guard against snark.

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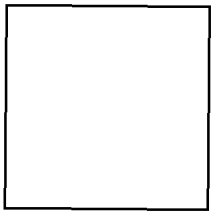

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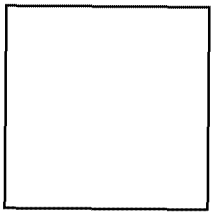

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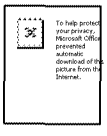

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Sent: 7/16/2025 8:18:11 PM
To: Ross McKitrick [ross.mckitrick@gmail.com]; John Christy [climateman60@gmail.com]
CC: Judith Curry [curry.judith@gmail.com]; Steven Koonin [steven.koonin@gmail.com]; Travis Fisher [travis.scott.fisher@gmail.com]; Josh Loucks [loucksj14@gmail.com]; Seth Cohen [seth.cohen@hq.doe.gov]
Subject: Re: NCA5 progress

Ross, regarding your idea about us going through sequentially.. should I now go through what Steve sent? -Roy

---

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I must be missing something. Our papers directly address the issues espoused by NCA5. We offer all the data and methods. Why should our work be suppressed?

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Sent from my iPhone

On Jul 11, 2025, at 1:16 PM, judith curry <curry.judith@gmail.com> wrote:

We need to think about our audience who we want to reach and influence. We don't want this to be another salvo in the climate wars. But to rise above it and be hyper objective.

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... Christy, McKitrick and Koonin ... you could look at it this way: we're the only ones willing to stick our heads up when the bullets are flying and endure protracted battles with editors and reviewers. Publishing in journals in this "climate" takes its toll, and most folks with an objective side just give up. We would love to cite other authors who do these NCA5-type analyses using the proper methods ... there just aren't many out there. As you know, there's no profit (or funding) in fighting the climate establishment. However, please, let us know if you see something we've missed.

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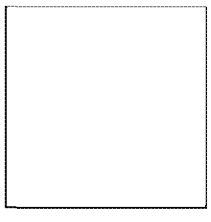

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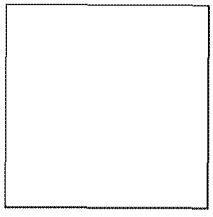

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From: Steven Koonin <steven.koonin@gmail.com>
Sent: Wednesday, July 16, 2025 6:30 AM
To: 'Judith Curry'; 'Ross McKitrick'
Cc: 'John Christy'; 'Travis Fisher'; 'Roy W. Spencer'; 'Josh Loucks'; 'Seth Cohen'
Subject: RE: NCA5 progress
Attachments: image001.jpg; NCA5Review Curry SK Curry SK.docx

And my further edits attached.

Do keep me at least cc'd over the next few days – I'll respond as I'm able.

SEK

From: Judith Curry <curry.judith@gmail.com>
Sent: Tuesday, July 15, 2025 7:05 PM
To: Ross McKitrick <ross.mckitrick@gmail.com>
Cc: John Christy <climateman60@gmail.com>; Steven Koonin <steven.koonin@gmail.com>; Travis Fisher <travis.scott.fisher@gmail.com>; Roy W. Spencer <roywspencer@hotmail.com>; Josh Loucks <loucksj14@gmail.com>; Seth Cohen <seth.cohen@hq.doe.gov>
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Here is my revised version. One proposed change of substance, relates to TX floods.

In section 8.3, i proposed modifying one of the bullets:

- The range of climatic and weather conditions, including extremes, that have occurred in the past and can reasonably be expected to occur in U.S. regions over the near future. An example of a salient acute failure is the NCA5 chapter (region that includesTexas) that fails to mention the historical occurrence and future risk of flash floods in the Texas Hill Country ROSS MAYBE MENTION WHAT NCA5 SAID ABOUT TX FLOODS in REGIONAL CHAPTER. THEN INCLUDE LINK TO YOUR MINI ANALYSIS

An alternative approach would be to add a new chapter on Failure to document the risk of extreme events based on the historical data base, something like that. Simpler just to mention it in Section 8.3

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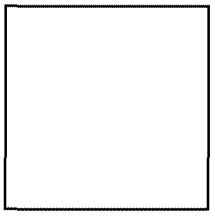

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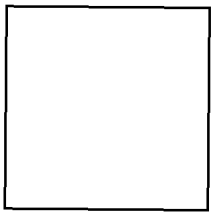

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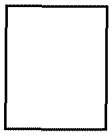

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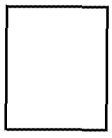

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Critique of the Fifth National Climate Assessment

EXECUTIVE SUMMARY 3

1 INTRODUCTION 4

1.1 About this Report 4
1.2 About the National Climate Assessments 4
1.3 Standards for Assessing NCA Products 5
1.4 When Peer Review Failed ..... Error! Bookmark not defined.

2 NCA5 OVERVIEW CHAPTER: HYPERBOLIC ADVOCACY LANGUAGE AND UNSCIENTIFIC TONE 6

3 OVERCONFIDENCE WHEN STATING CONCLUSIONS 7

3.1 Inflated certainty levels 7
3.2 Overstating findings in underlying sources 9
3.3 Technical example: Emergent constraints 9

4 ARBITRARY AND AMBIGUOUS TREND ANALYSIS 10

4.1 Average and Extreme Precipitation 11
4.2 Heatwaves 11

5 INADEQUATE TRACEABLE ACCOUNTS 14

6 OVEREMPHASIS ON EXTREME SCENARIOS 16

7 CONFLATION OF NATURAL AND ANTHROPOGENIC CLIMATE CHANGES 18

8 SUMMARY EVALUATION OF NCA5 AND RECOMMENDATIONS FOR NCA6 19

8.1 Compliance with USGCRP's statutory obligation 19
8.2 Adherence to the tenets of Gold Standard Science 20
8.3 Suitability for informing Federal climate and energy policy 20
8.4 Recommendations for NCA6 22

9 REFERENCES 23

APPENDICES ..... ERROR! BOOKMARK NOT DEFINED.

APPENDIX 1: Charge to the review 24

ABOUT THE AUTHORS 25

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EXECUTIVE SUMMARY

This report critically evaluates the Fifth National Climate Assessment (NCA5), finding it an inadequate basis for climate and energy policies. A detailed review of the foundational chapters on climate science raises several key concerns:

Scientific Integrity

- An advocacy tone, particularly in the Overview chapter, that is inconsistent with scientific objectivity
- Framing climate policy as a morality play
- Endemic overconfidence when stating conclusions, including inflated certainty levels and overstatement of findings from underlying sources
- No mentions of dissent, disagreement, controversies, or tradeoffs

Flawed methodology

- Minimal discussion of observational inadequacies
- Use of short time periods for trend analyses; lack of a consistent rationale for choosing time scales
- Attribution is implied, not dissected
- Overemphasis on extreme scenarios for future emissions and sea level rise
- Inadequate traceable accounts to support key conclusions

Inadequate Review Process

- A review by the National Academy of Sciences, Engineering, and Medicine (NASEM) failed to identify some fundamental flaws in NCA5
- The NCA5 authors failed to adopt some improvements recommended by NASEM

The report shows NCA5 to be a biased and incomplete picture of climate science that skews toward excessive climate risk. Consequently, NCA5 should not be used as basis for climate and energy policies.

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1 INTRODUCTION

1.1 About this Report

This report responds to a request from the Office of Science and Technology Policy (OSTP) Director Michael Kratsios (reproduced in the Appendix) [MAY HAVE TO MODIFY THIS] that we assess the suitability of the Fifth National Climate Assessment (NCA5 2023) for informing climate and energy policies.

To conduct this assessment, we reviewed NCA5 itself, the National Academies of Science, Engineering and Medicine (NASEM) review of the Third Order NCA5 Draft, and the USGCRP responses to that review. We have drawn upon our long experience working on advisory reports, including for the NASEM, the Intergovernmental Panel on Climate Change (IPCC), and other organizations as writers, reviewers, and study leaders. Further, we have reviewed recent scientific developments in a separate report to Energy Secretary Wright (Climate Working Group 2025, herein denoted "CWG25").

We find that NCA5 should not be relied on for policy making as it is an incomplete and misleading picture of our understanding of the changing climate and the risks it poses to the nation. NCA5 was selective and incomplete in its survey of climate science. The overall effect of the biases and omissions of NCA5 is an excessively dire picture of climate risk.

To support our finding, the following sections of this chapter provide some background on the National Climate Assessments and the standards by which we have assessed NCA5. Chapters 2 through 7 detail important ways in which NCA5 fails to meet those standards. Finally, Chapter 8 summarizes our evaluation of NCA5 and makes recommendations for NCA6.

1.2 About the National Climate Assessments

The U.S. Global Change Research Program (USGCRP) was established by Presidential Initiative in 1989 and mandated by Congress in the Global Change Research Act (GCRA) of 1990 to develop and coordinate "a comprehensive and integrated United States research program which will assist the Nation and the world to understand, assess, predict, and respond to human-induced and natural processes of global change."

The National Climate Assessment (NCA) Reports evolved from the GCRA requirement to:

> Prepare and submit to the President and the Congress an assessment which (1) integrates, evaluates, and interprets the findings of the Program and discusses the scientific uncertainties associated with such findings; (2) analyzes the effects of global change on the natural environment, agriculture, energy production and use, land and water resources, transportation, human health and welfare, human social systems, and biological diversity; and (3) analyzes current trends in global change, both human-induced and natural, and projects major trends for the subsequent 25 to 100 years.

The five NCA Reports to date have interpreted this mandate in different ways:

- NCA1 (2000) was a multidisciplinary effort to study and portray in regional detail the potential effects of human-induced global warming on the United States.

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- NCA2 (2009) was a relatively short report that not only focused on the potential consequences of climate change but also sought to identify potential adaptation measures and identify the highest priorities for future research.
- NCA3 (2014) was an expanded effort that continued along the lines of NCA2, and was distinguished by a comprehensive review process, including a review by the National Academy of Sciences. NCA3 introduced a traceability analysis for each key finding, including a description of uncertainties.
- NCA4 (2017/2018) was a further expanded effort that was published in two volumes: I Climate Science Special Report (CSSR), and II Impacts, Risk, and Adaptation in the United States. This was the first NCA report to devote significant effort to assessing climate science.
- NCA5 (2023) returned to a single volume format, reducing discussion of climate science to a cursory two chapters, with continuing focus on regional and sectoral impacts of climate change. NCA5 expanded its remit to topics that are arguably outside the purview of the USGCRP, focusing on "Climate Action" and policy recommendations with a social justice emphasis.

These successive interpretations of the NCA are poorly aligned with the GCRA's statutory requirements. Only NCA4 gives serious consideration to climate science, which receives the great majority of USGCRP funding, and even then NCA4 misrepresents some important points. Natural climate variability is essentially dismissed as unimportant in NCA4 and barely mentioned in NCA5 in most contexts, despite the mandate to include both human-caused and natural climate change. Most significantly, NCA5 has redirected the focus away from climate science and even the hazard elements of impacts, towards evaluation of societal vulnerabilities and advocacy for particular policy options, especially deployment of wind and solar power generation.

1.3 Standards for Assessing NCA Products

Beyond the statutory requirements stated above, another pertinent standard is President Trump's executive order of May 23, 2025, Restoring Gold Standard Science. It enumerates some of the characteristics of good science, namely that it should be:

i. reproducible;
ii. transparent;
iii. communicative of error and uncertainty;
iv. collaborative and interdisciplinary;
v. skeptical of its findings and assumptions;
vi. structured for falsifiability of hypotheses;
vii. subject to unbiased peer review;
viii. accepting of negative results as positive outcomes; and
ix. without conflicts of interest.

For an assessment of policy relevant science, it is also important to include statements about the strength of knowledge. The IPCC's approach to assessing strength of knowledge is based on judgment of the available evidence and agreement among experts. But there are more sophisticated knowledge characterizations for risk management. Here are the elements according to Aven (2017):

- The degree to which the assumptions made are reasonable/realistic based on background knowledge

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- The degree to which data/information exists and are reliable and relevant
- The degree to which there is disagreement among experts (including those from different environments or academic fields)
- The degree to which the phenomena involved are understood and accurate models exist
- The degree to which the knowledge has been thoroughly examined with respect to unknown knowns (issues that are known to matter but are ignored, such as, in this context, natural variability).

2 NCA5 Overview Chapter: Advocacy language and unscientific tone

NCA5 Chapter 1, "Overview", holds a prominent place in the Report since it summarizes the entire report and is the only section that many will read. Chapter 1 is marred by an activist tone, language that aggressively promotes mitigation policies, and motivated optimism. As such, this chapter adds an imprimatur of scientific authority to naïve and simplistic declarations of opinion about public policy. Here are some examples.

Chapter 1 opens with:

> The more the planet warms, the greater the impacts. Without rapid and deep reductions in global greenhouse gas emissions from human activities, the risks of accelerating sea level rise, intensifying extreme weather, and other harmful climate impacts will continue to grow. Each additional increment of warming is expected to lead to more damage and greater economic losses compared to previous increments of warming, while the risk of catastrophic or unforeseen consequences also increases.

This statement presupposes that all warming is anthropogenic, that all warming is bad and causes economic damage, and that warming intensifies extreme weather. Such sweeping generalizations go well beyond what science has or can establish. The statement also refers to growing risks without reference to their magnitude – a small risk that increases might still be a small risk, and a large risk might be only incrementally worsened.

On the next page one finds:

> Each additional increment of warming leads to greater risks [here it lists 7 key components of society including food security and the economy] ... Without deeper cuts in global net emissions, climate risks to the US will continue to grow... Action to limit future warming and reduce risks can have near-term benefits and opportunities: low-carbon energy jobs, Improved air quality, Health benefits, Economic benefits..."

The authors write as if climate policy does not involve trade-offs and all measures to reduce future warming will be effective and beneficial. Neither the vast body of scholarship on climate science and economics nor historical experience support such simplistic claims (CWG25). Not every additional increment of warming leads to economic harms; in fact, NCA5 Chapter 19 acknowledges that there will also be benefits. Nor is climate policy guaranteed to benefit the economy; it could impose net costs. Such misleading statements are a disservice to policymakers.

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Pages 8 and 9 of the Overview promote renewable energy options by noting, correctly, that the levelized costs of wind/solar generation have fallen sharply since 2010, and so offers this rationale for pursuing deep emission reductions:

> Recent growth in the capacities of wind, solar, and battery storage technologies is supported by rapidly falling costs of zero- and low-carbon energy technologies, which can support even deeper emissions reductions. For example, wind and solar energy costs dropped 70% and 90%, respectively, over the last decade, while 80% of new generation capacity in 2020 came from renewable sources.

Yet it has long been known that intermittent renewables generation must be supplemented by dispatchable generation to meet grid reliability standards, and that doing so (*e.g.*, through natural gas, fission, or storage) significantly increases the total cost of electricity. Further, there are yet unmet synchronization challenges in electrical grids with heavy penetration of wind and solar generation. NCA5 fails to acknowledge these facts. But more importantly, we see no reason for NCA5 to be discussing renewable energy technologies and economics in the context of its mandate.

Page 17 of the Overview introduces the discussion of risks from extreme weather events by saying "Harmful impacts from more frequent and severe extremes are increasing across the country." This creates the impression that extreme weather events are worsening and that disaster losses are driven by trends in extreme weather. While the section goes on to acknowledge that some of the increase is due to increases in the exposure and value of assets at risk, it then invokes the NOAA Billion Dollar Dataset as evidence of extreme weather getting worse. Scientists have shown that this is an invalid metric (CWG25 Section 10.2) since it measures the growth of the economy, not the frequency of extreme weather, and indeed NOAA has recently withdrawn the data product. Even though the dataset was still distributed by NOAA at the time of the NCA5, the report authors failed to assess it skeptically and see that it was unfit for the purpose of measuring climate trends.

Page 23 of the Overview states, in large font:

> Climate changes are making it harder to maintain safe homes and healthy families; reliable public services; a sustainable economy; thriving ecosystems, cultures, and traditions; and strong communities.

This statement cannot be evaluated on scholarly grounds and so doesn't belong in a scientific assessment report. Its prominent inclusion points not only to the willingness of NCA5 authors to promote alarm, but also the ineffectiveness of the review process in eliminating such statements.

3 OVERCONFIDENCE WHEN STATING CONCLUSIONS

3.1 Inflated certainty levels

Overconfidence in stating conclusions has been an endemic problem in NCA Reports. The authors frequently make sweeping generalizations without appropriate caveats or acknowledging uncertainties. The overconfidence begins with inflated language to describe certainty levels.

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NCA5 uses specific terms to convey information about scientific confidence associated with important finds, observations and projections. The Front Matter of NCA5 states that

> confidence in a finding is based on the type, amount, quality, strength, and consistency of evidence; the skill, range, and consistency of methods to detect, evaluate, attribute, and interpret climate trends; and the degree of agreement across scientific information sources.

Table 1 from the Front Matter provides calibrated language for confidence assessments:

Very high:	Strong evidence (established theory, multiple sources, well documented and accepted methods, etc.). High consensus
High:	Moderate evidence (several sources, some consistency, methods vary and/or documentation limited, etc.). Medium consensus
Medium:	Suggestive evidence (a few sources, limited consistency, methods emerging, etc.) Competing schools of thought.
Low:	Inconclusive evidence (limited sources, extrapolations, inconsistent findings, poor documentation and/or methods not tested, etc.). Disagreement or lack of opinions among experts.

This terminology is obviously inflated: *high confidence* with just moderate evidence and medium consensus; *medium confidence* with only suggestive evidence and competing schools of thought. This inflation in terminology leads to overconfidence in conclusions.

Even with this inflated terminology, NCA5 further inflates the confidence level of many of its conclusions to well beyond what the IPCC has concluded with more thorough justification, and by incorrectly applying its own standards. An example is the conclusion about anthropogenic influence on climate change, arguably one of the most important scientific statements of the report.

Key Message 3.1 Traceable Account states:

> There is *very high confidence* that emissions of GHGs from human activities, fossil fuel use in particular, have unequivocally caused *all* global warming observed over the industrial era.

while the corresponding statements from IPCC AR5 and AR6 are

> **AR5:** It is *extremely likely* that *more than half* of the observed increase in global average surface temperature from 1951 to 2010 was caused by the anthropogenic increase in greenhouse gas concentrations and other anthropogenic forcings together. (IPCC, 2013)

> **AR6:** The *likely* range of total human-caused global surface temperature increase from 1850–1900 to 2010–2019 is 0.8°C to 1.3°C, with a best estimate of 1.07°C. It is *likely* that well-mixed GHGs contributed a warming of 1.0°C to 2.0°C, other human drivers (principally aerosols) contributed a cooling of 0.0°C to 0.8°C, natural drivers changed global surface temperature by –0.1°C to +0.1°C, and internal variability changed it by –0.2°C to +0.2°C. It is *very likely* that well-mixed GHGs were the main driver of tropospheric warming since 1979.

The IPCC AR5 and AR6 statements provide likelihood assessments but not a confidence level. While NCA5 claims with *very high confidence* that fossil fuels have unequivocally caused *all* global warming, AR5 refers to "*more than half* of the observed warming" and AR6 provides a more nuanced statement that relates to a *likely* range of warming contributed to by human drivers.

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3.2 Overstating findings in underlying sources

Although we did not do a detailed audit of NCA5's use of source material, spot checks suggest a pattern of overstatement.

Chapter 2 page 11 reports on an increase in precipitation in some areas and attributes it to "climate change":

> Many eastern regions of the country are getting wetter (Figure 2.4). Average annual precipitation from 2002-2021 was 5%-15% higher relative to the 1901-1960 average in the central and eastern US, a trend attributable to climate change.

NCA5 attributes the claim to Knutson and Zeng (2018). But Knutson and Zeng did not say these things nor did they analyze this particular period. For 1981-2010 they cautioned that observed changes are consistent with natural variability, and they did not claim attributable trends were observed over the United States.

As another example of overstating findings, NCA5's Chapter 2 page 18 states

> There is robust evidence that human-caused warming has contributed to increases in the frequency and severity of the heaviest precipitation events across nearly 70% of the US.

This is apparently attributed to Diffenbaugh *et al.* (2018) and Kirchmeier-Young and Zhang (2020). Diffenbaugh *et al.* presented ratios of observed occurrences of extreme events to simulated occurrence rates in CMIP6 models run with only natural forcings. They report that for 79% of the U.S., extreme rainfall events are currently more frequent than in simulations, and the ratio of occurrences will rise under future warming simulations. This is not "robust" evidence of anthropogenic influence since it requires readers to assume that climate models accurately simulate regional precipitation patterns, something that the IPCC AR6 states is uncertain (AR6 WGI SPM Box SPM 1.2, SPM Section C.1.3).

Kirchmeier-Young and Zhang used three global climate models to analyze extreme 1- and 5-day events in North America. They noted large differences among the three models in their simulated precipitation changes, and two of the three models failed to yield attribution for 5-day events for the North America mean.[DON'T UNDERSTAND THIS PHRASE] THIS IS CLEAR, KEEP AS IS MIGHT MAKE SENSE TO ME IF WORDED AS "for the North American mean of 5-day events." In other words, the models disagreed on whether the observed changes were anthropogenic. Both of the cited references utilized the implausible RCP8.5 scenario (Chapter 6 of this report) and began their historical observational records only in 1961. Here again this is not "robust" evidence. It is merely suggestive, particularly since other studies have found natural variability to be predominant.

3.3 Example: Emergent constraints

Some of the overconfidence expressed by NCA5 arises by omitting discussion of counterevidence in the peer reviewed literature, ignoring dissent and disagreement. An example is the topic of "emergent constraints". NCA5 Chapter 3 page 17 invokes this concept to support its claim that key uncertainties in climate model projections have been reduced:

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> An approach to reduce uncertainty in climate change projections has matured over the past decade. It is known as "emergent constraints." The term refers to strong statistical relationships between highly uncertain future climate parameters and observable trends or variations in the current climate, along with a physical explanation of this relationship.

Emergent constraints appeared in the climate modeling literature as an attempt to tie climate model behavior to climate observations in hopes of generating insight into real-world equilibrium climate sensitivity (ECS). Climate models exhibit a wide range of ECS values. The idea of emergent constraints is to examine whether the models with shared sensitivity values also share a common representation of some climate process (usually related to clouds) that might influence ECS. Suppose, for example, that in low-ECS models the total cloud fraction in the tropics is strongly correlated with that in the southern midlatitudes, but in high-ECS models the correlation is weak. Then researchers could examine whether the observed correlation is strong or weak and draw a conclusion about which type of model, and therefore which ECS value, is more likely.

A problem in the emergent constraint literature is that there has been a proliferation of proposed correlations with little physical motivation. NCA5 alludes to this in the Traceable Accounts section (p. 3-40) but not in the main chapter text. As shown by Schlund *et al.* (2020), many emergent constraints patterned on CMIP5 models (Coupled Model Intercomparison Project Phase 5, used for the IPCC 5th Assessment Report) failed to work on CMIP6 models (used for the IPCC 6th Assessment Report). In other words, the correlations between ECS and cloud processes present in CMIP5 models were absent in CMIP6 models, indicating that they were likely spurious rather than clues to physical processes governing the climate system. As a result, emergent constraints estimated on CMIP5 models *increased* the uncertainty of ECS, rather than decreasing it as claimed by NCA5.

Yet NCA5 described the use of emergent constraint analysis as an advance that reduced the uncertainty of ECS and climate model projections (p. 3-38):

> Emergent constraints have been widely applied to reduce the simulated spread in the climate feedbacks that shape climate sensitivity.

4 ARBITRARY AND AMBIGUOUS TREND ANALYSES

CWG25 Chapter 6 discussed the need for care in the choice of time scale when making claims about trends in extreme weather. We provided examples from analysis of river flooding, heatwaves, and extreme precipitation to show how assertions about apparent trends based on short data sets fall apart when considering longer versions of the same data sets. NCA5 uses varying time periods for trend analyses, especially in Chapter 2 (which is focused on trends), without explaining why shorter or longer intervals were chosen. For example, page 2-4 defines temperature trends over the interval since the late 1800s whereas page 3-29 presents temperature trends over 1972-2021. Page 2-11 compares rainfall over the 2002-21 versus 1901-1960 intervals, while page 2-18 uses the interval since the late 1950s to compute trends.

A further problem is that NCA5 uses the term "trend" repeatedly without indicating if it is statistically significant (*i.e.*, distinguishable from random variability); the ambiguity creates the impression all the observed changes were significant, but readers are left to speculate. All climate variables will, in principle, drift up or down over any particular time interval. Identifying the change as a trend requires showing that it is statistically significant using a variance estimator suitable for the type of

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data being analysed. Of particular importance is choosing a method robust to the serial correlation that is frequently present in climate data. Throughout Chapters 1 to 3, references are made to "trends" without explaining how they were computed. The exception was on page 1-19 which refers to urban temperature trends being calculated using the Theil-Sen estimator, although that method does not seem to have been used elsewhere. The one case where reference is made to statistical significance is on Page 2-9, referring to a trend in Atmospheric Optical Depth, but there is no explanation of how significance was determined. Page 2-19 refers to regional trends in droughts being "robust" but again fails to explain how the term was defined.

4.1 Average and Extreme Precipitation

CWG25 Section 6.4 we presented analyses of updated data for the same locations [SAME AS WHAT?] (and many others), in all cases finding both considerable regional heterogeneity and that trends detectable on one time scale are often not detected on longer or shorter time scales. These findings argue against simple attribution of changes to anthropogenic influences. In this section, when we refer to calculation of trends in precipitation, we use ordinary least squares to compute the linear trend over the entire sample length and we use the Vogelsang and Franses (2007) variance estimator which is robust to general forms of serial correlation. IS THIS STATEMENT NEEDED?

NCA5 did not continue the NCA4 precedent of using the post-1901 interval as the time scale for its precipitation discussion. Instead, it refers to changes "since the 1950s"; NCA5 Figure 2.8 suggests 1958 might be the intended start date. Under Key Message 2.2, "Extreme Events Are Becoming More Frequent and Severe", NCA5 states (p. 2-18):

> Rainfall is becoming more extreme
> Since the 1950s, there has been an upward trend in heavy precipitation across the contiguous US. This increase is driven largely by more frequent precipitation extremes, with relatively smaller changes in their intensity.

In addition to our concerns that inferences about trends are contingent on choice of time scale, if the intended meaning of this statement is that positive and significant trends are found in heavy precipitation events across CONUS, we cannot reproduce it. Details of our analysis can be found at LINK TO BRIEF WRITEUP ON THIS can we just reference CWG HERE

Based upon our analysis, the following is a more accurate summary of what U.S. precipitation data show.

> There are regionally heterogenous changes in average and extreme precipitation. Positive trends in annual average rainfall and extreme events (defined either as the annual maximum or the number of exceedances of the 99th percentile value) are generally weak or non-existent when looking at samples exceeding 130 years in length. Significant trends can be found when beginning the sample in the 1950s although in most cases the trends weaken and become insignificant when looking at the post-1980 interval. This argues against attribution of changes in precipitation to anthropogenic warming.

4.2 Heatwaves

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In contrast to NCA5, NCA4 examined heat extremes across the entire 20th century, pointing out that peak heat wave activity was reached in the 1930s and has decreased since then, and that recent increases are confined to areas west of the Rockies. NCA4 stated:

> [The] warmest daily temperature of the year increased in some parts of the West over the past century, but there were decreases in almost all locations east of the Rocky Mountains. In fact, all eastern regions experienced a net decrease, most notably the Midwest (about 2.2°F [1.2°C]) and the Southeast (roughly 1.5°F [0.8°C]).
>
> Since the mid-1960s, there has been only a very slight increase in the warmest daily temperature of the year (amidst large interannual variability). Heat waves (6-day periods with a maximum temperature above the 90th percentile for 1961–1990) increased in frequency until the mid-1930s, became considerably less common through the mid-1960s, and increased in frequency again thereafter. As with warm daily temperatures, heat wave magnitude reached a maximum in the 1930s.
> (NCA4 pp. 190-191)

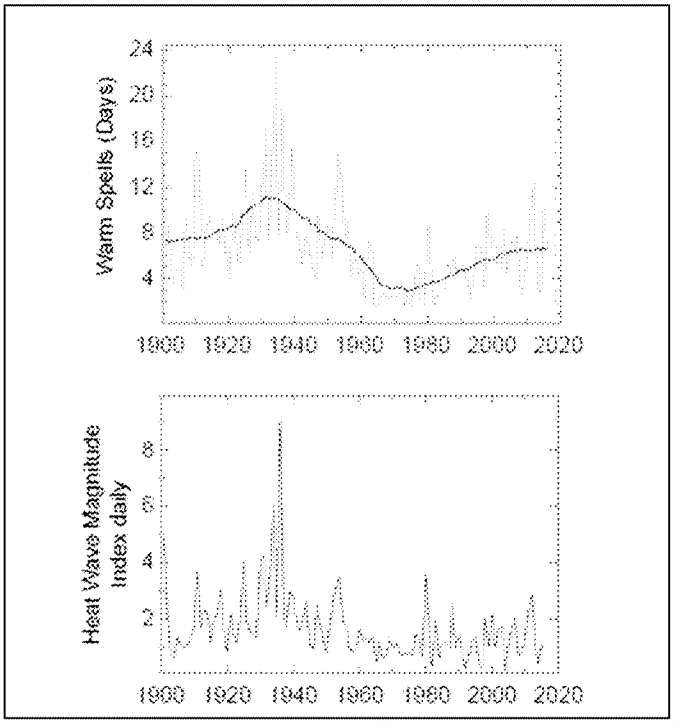

FIGURE 3. U.S. Heat waves since 1900. Reproduction of NCA4 Figure 6.4

Contrast this careful and factual language from NCA4 with NCA5 Key Message 2.2: "Extreme Events Are Becoming More Frequent and Severe." This blanket statement is followed by NCA5 Figure 2.7 (reproduced as Figure 4 below) which shows the number of hot days, cold days and warm nights (respectively in panels a—c) over the period 2002-2021 compared to 1901-1960. [Presumably these are annual counts, although not stated in the caption.]

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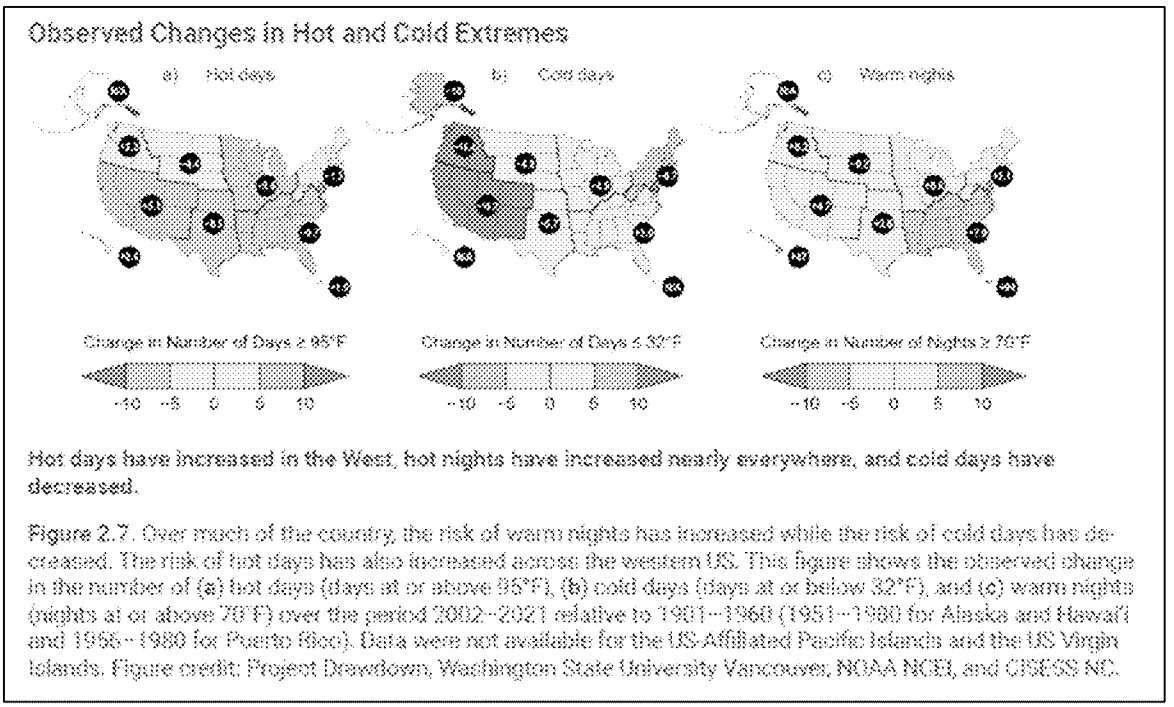

Figure 2.7. Over much of the country, the risk of warm nights has increased while the risk of cold days has decreased. The risk of hot days has also increased across the western US. This figure shows the observed change in the number of (a) hot days (days at or above 95°F), (b) cold days (days at or below 32°F), and (c) warm nights (nights at or above 70°F) over the period 2002–2021 relative to 1901–1960 (1951–1980 for Alaska and Hawai'i and 1956–1980 for Puerto Rico). Data were not available for the US-Affiliated Pacific Islands and the US Virgin Islands. Figure credit: Project Drawdown, Washington State University Vancouver, NOAA NCEI, and CISESS NC.

FIGURE 4: Reproduction of NCA5 Figure 2.7.

Close inspection shows that this figure actually contradicts the NCA5 Key Message with respect to heatwaves and instead reinforces the position of NCA4. Notwithstanding Key Message 2.2, the leftmost panel in NCA5 Figure 2.7 above shows that over most of CONUS the number of extreme heat days has *decreased* in recent decades compared to the prior century.

The accompanying discussion in NCA5 becomes convoluted as it appears to be aimed at supporting the Key Message despite the contrary evidence. NCA5 Chapter 2 elaborates on Key Message 2.2 by stating (page 2-16):

> Observations show an increase in the severity, extent, and/or frequency of multiple types of extreme events. Heatwaves have become more common and severe in the West since the 1980s (*high confidence*).

But while it mentions the increase in hot days in the West, it fails to mention the decrease everywhere east of the Rockies. On the next page (page 2-17) it raises the comparison to the 1930s and then switches to discussing global counts:

> By some measures, the most extreme heatwaves on record in the United States occurred during the Dust Bowl era of the 1930s. ... Globally such heatwaves are becoming more frequent, and in recent decades the western United States has been following those trends.

The reference to a global trend seems to be an attempt to tie heatwaves to anthropogenic climate change. But the obvious question, unaddressed by NCA5, is why one region follows the global pattern of increasing heatwaves while most of the country is trending in the opposite direction. These issues are addressed in Chapter 6 of CWG25, demonstrating that the range and magnitude of extreme temperatures are driven more by natural variability than by anthropogenic forcing. The analysis in CWG25 shows that for both (a) hot days (≥ 95°F) and (b) number of days in heatwaves, the current decade is no hotter than a century ago in the U.S. Thus, the NCA5 claim that "multiday heatwaves

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have become hotter, more frequent, larger, and longer lasting in recent decades," is simply false when expanding the temporal and spatial domains to encompass all available data (Chapter 6 and Figure 6.3.6 of CWG25).

NCA5 then pointed to the dramatic Pacific Northwest heatwave of 2021. CWG25 Section 8.6.1 discusses this event in detail, reviewing the multiple peer reviewed studies that explained the unusual meteorological context was unrelated to human-caused climate change, a point omitted from the NCA5 discussion.

NCA5 finally addresses the declining heatwave trend in CONUS east of the Rockies but attempts to reframe it by focusing on urban warm spells.

> [The] number of very hot days has actually decreased across the central and eastern regions due to summer cooling trends in the region (Figure 2.7; Ch. 22). This does not, however, mean the central and eastern US are not affected by heat. The impacts of extreme high temperatures are more severe if such conditions persist for several days, and overall, multiday heatwaves have become hotter, more frequent, larger, and longer lasting in recent decades. Across 50 large US cities, the US Global Change Research Program heatwave indicator (https://www.globalchange.gov/indicators/heat-waves) shows that the average number of heatwaves has doubled since the 1980s, and the length of the heatwave season has increased from about 40 days to about 70 days.

We discussed this part of NCA5 in CWG25 Section 6.3. The figure referenced by NCA5 uses a short time period which begins in the 1960s, the coldest decade in the last 100 years, thus suppressing any comparison to the 1930s. Further, nighttime temperatures in urban areas have increased faster than daytime temperatures (which NCA5 acknowledges), but this is a signature of urban heat islands and not a good metric of climate change. CWG25 found that the occurrence of hot days (≥ 95° F) has recently increased in the West, but declined since 1899 in the remainder of the country and in the nationwide average.

5 INADEQUATE TRACEABLE ACCOUNTS

NCA3 began the practice of including a section on Traceable Accounts at the end of each chapter. This is the description from NCA5:

> Each chapter concludes with a section entitled Traceable Accounts, which provides information on the overall process used to develop the chapter as well as a separate Traceable Account section for each Key Message. These Traceable Accounts describe the supporting evidence behind each Key Message, the process and rationale authors used in reaching their conclusions, and the author team's expert assessment of the confidence in and, where applicable, likelihood of these conclusions. As such, Traceable Accounts provide information about the state of the science, document sources of uncertainty, identify research gaps, and allow traceability to data and resources.

The Traceable Accounts for each Key Message includes the following sections:

- Description of Evidence Base
- Major Uncertainties and Research Gaps

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- Description of Confidence and Likelihood

The Traceable Accounts could have addressed the statutory requirement that the NCA discuss scientific uncertainties. They could also help satisfy the Executive Order for Restoring Gold Standard Science by addressing reproducibility, transparency, communication of error and uncertainty, and skepticism of findings and assumptions. However, the Traceable Accounts in NCA5's Chapters 2 and 3 are uneven, often superficial and uninformative.

An example of a deficient Traceable Account is NCA5's Key Message 2.2: "Extreme Events are Becoming More Frequent and Severe". The "Description of the Evidence Base" offers two paragraphs, the first summarizing the findings and the second generically describing the types of data that can be used for storms. "Major Uncertainties and Research Gaps" focuses on the uneven distribution across U.S. populations due to differences in exposure and vulnerability. The only limitations in data referred to are the lack of a long-term record of lightning and the lack of homogenized daily and hourly temperature data apart from reanalysis products.

But the most astonishing deficiency is in the "Description of Confidence and Likelihood." One of the statements in Key Message 2.2 is:

> Hurricanes have been intensifying more rapidly since the 1980s (*high confidence*) and causing heavier rainfall and higher storm surges (*high confidence*).

The Description of Confidence and Likelihood includes the following statement:

> Basic physical understanding and climate models both provide robust explanations for the links between climate change and observed changes in these extremes: this is why the authors also have high confidence that storms are delivering more rainfall and high confidence that storm surges are becoming higher.

No reference to journal publications or a specific data set is made anywhere in the chapter regarding hurricane-induced precipitation or storm surge to support this *high confidence* conclusion.

The Traceable Accounts for the various Key Findings of Chapter 3 have some substantial inconsistencies. Consider

> Key Message 3-1: Human activities have caused global warming.
> Confidence and Likelihood: "There is *very high confidence* that emissions of GHGs from human activities, fossil fuel use in particular, have *unequivocally* caused all global warming observed over the industrial era. There is also *very high confidence* that changes in natural climate drivers have had globally small and regionally variable long-term effects over this period."

The Uncertainties section addresses only uncertainties in radiative forcing by greenhouse gases, ignoring the great uncertainty in model response (CWG25 Chapters 4 and 5) In contrast, the Traceability Analysis of Key Message 3-4 ("Humans Are Changing Earth System Processes") raises the problem that relatively little is known about the role of natural variability at the regional scale. From its Description of Evidence Base:

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> In the last decade, there has been increasing recognition of the role of regional-scale natural variability in the past and future evolution of climate, as well as the fact that regional natural variability signals can be competitive with forced anthropogenic signals.

And from its Major Uncertainties and Research Gaps:

> For example, the true natural variability of the climate system on decadal to centennial timescales could be larger than what we estimate from GCMs, which would further increase the irreducible uncertainty stemming from natural variability.

These statements are among the most scientifically credible in the entire NCA5 and they directly undercut the confidence assigned to Key Message 3-1.

There is also a generic problem in tracing NCA5's Traceable Accounts. The Front Matter of NCA5 states:

> Each figure and some tables are accompanied by a metadata survey, which can be accessed in the online version of the report by clicking on the eyeball icon above the figure or table (see the table below for explanations of additional icons used throughout the report). The metadata survey describes data sources, figure or table development methods, copyright information, and other important documentation.

Clicking on the 'eyeball' icon does not reveal the metadata information; instead a "Contact Us" email appears, addressed to the USGCRP. This is an inadequate way to archive the metadata information.

In summary, the Traceable Analyses examined here, with few exceptions, fail to meet the stated objectives of the NCA.

6 Overemphasis on Extreme Scenarios

To respond to the GCRA mandate to "project major trends for the subsequent 25 to 100 years," NCA5 relies on projections of future climate change based on estimates of future emissions (the so-called SSP scenarios) and/or specified levels of radiative forcing (the RCP scenarios). For the most part, NCA5 uses scenarios developed for the IPCC Assessment Reports.

CWG25 Section 3.2.1 presented a critical assessment of past and current IPCC scenario envelopes, showing that they have tended to overshoot observed emissions. IPCC AR6 published in 2021 stated that "The likelihood of high-emission scenarios like RCP8.5 and SSP5-8.5 is considered low in light of recent energy sector developments." and that same year UN Climate Negotiators (COP) stopped using scenarios above 4.5.

NCA5 makes the following observations about the scenarios they use:

> NCA5 authors were advised to assess the full range of scenarios available. (Front Matter)

> Scenarios of future emissions and land-use change are developed as plausible alternatives, but no relative likelihood is attached to them. Some recent studies, however, have argued that

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the highest scenario, SSP5-8.5, is no longer plausible without a reversal of current trends in the adoption of renewables and energy efficiency. (Key Message 3.3 Traceable Analysis)

Despite acknowledging the issue, NCA5 otherwise ignored the problem. A keyword search of NCA5 of mentions of RCP/SSP scenarios finds over 50% referred to the extreme emissions scenarios RCP8.5/SSP5-8.5. Further, nine NCA5 figures (5.2, 6.9, 7.4, 11.3, 14.6, 22.13, 22.19, 27.9, 29.13) included *only* the 8.5 scenarios.

The problem of relying on extreme scenarios is particularly acute for NCA5's sea level rise projections. The sea level rise scenarios used in NCA5 do not relate directly to the SSP emissions scenarios, but rather to specified amounts of sea level rise by 2100. Table 4 of NCA5's "Guide to Using this Report" reproduced below shows that Low relates to 0.3 m (0.98 feet), Intermediate-Low relates to 0.5 m (1.64 feet), Intermediate relates to 1.0 m (3.28 feet), Intermediate-High relates to 1.5 m (4.92 feet), and High relates to 2.0 m (6.56 feet).

Table 4. Descriptive Terms for Common Sea Level Rise Scenarios Used in NCA5

Future global mean sea level rise and sea level rise along United States coastline are shown for five scenarios in feet (and meters), relative to a 2000 baseline. The US values shown in the right half of the table are averaged across the US coastal regions, including the contiguous US, Alaska, Hawai'i and the US-Affiliated Pacific Islands, and the US Caribbean. The national values shown in the table differ substantially from regional values. For example, sea level rise is higher in the Gulf Coast and lower or even negative in some parts of Alaska. In the next 30 years (2020–2050), sea level along the contiguous US coasts is expected to rise 0.92 feet (0.28 m), the same amount of sea level rise observed over the last 100 years (1920–2020). See Chapter 9 for regional sea level information. Adapted from Sweet et al. 2022.[7]

Sea Level Rise Scenario Descriptor	Global Mean Sea Level			United States		
Year	2050	2100	2150	2050	2100	2150
Low	0.49 (0.15)	0.98 (0.3)	1.31 (0.4)	0.59 (0.18)	0.98 (0.3)	1.64 (0.5)
Intermediate-Low	0.66 (0.20)	1.64 (0.5)	2.62 (0.8)	0.75 (0.23)	1.64 (0.5)	2.95 (0.9)
Intermediate	0.92 (0.28)	3.28 (1.0)	6.23 (1.9)	0.89 (0.27)	3.28 (1.0)	6.89 (2.1)
Intermediate-High	1.21 (0.37)	4.92 (1.5)	8.86 (2.7)	1.12 (0.34)	4.92 (1.5)	8.86 (2.7)
High	1.41 (0.43)	6.56 (2.0)	12.14 (3.7)	1.38 (0.42)	6.56 (2.0)	12.46 (3.8)

TABLE 1: Reproduction of Table 4 from the Front Matter of NCA5

Considering only projections representing processes quantified with at least medium confidence, IPCC AR6 assessed global mean sea level projections for all emissions scenarios (including implausible extreme emissions scenarios) for 2100 to fall between 0.2 and 1.6 m (5th—95th percentile range). Nevertheless, the range of sea level rise scenarios considered by NCA5 extends to 2.0 m. Further, NCA5 fails to include plausible lower scenarios, such as 0.2 m cited by the IPCC, which also corresponds to the average rate of sea level rise over the past century.

Chapter 9 of NCA5 offers the following predictions of sea level rise:

> "Under a range of potential global warming levels, average sea level along US coastlines is *likely* to be between 12 and 20 inches above 2000 sea levels in 2050 (Figure 9.2)."

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The projected sea level rise values span from the Intermediate scenario to values slightly greater than the High scenario. They can be put into context by considering the observed global sea level rise from 2000-2024, which is only approximately 3.4 inches (0.28 feet). NCA5 is thus projecting a sea level rise during 2025 and 2050 that is 3.5 to 5.8 times the rate observed during 2000-2024, an exceedingly implausible outcome. Chapter 9 further states:

> "Looking toward the future, an 11 inch (28 cm) average rise along the contiguous US coastline is expected by 2050 (relative to 2020), with a *likely* range of 9-13 inches."
> ...
> "There is *high confidence* and it is *likely* that sea levels will rise about 11 inches (likely range of about 9–13 inches) between 2020 and 2050"

In summary, NCA5 presents future sea level rise scenarios that are not directly relatable to either SSP/RCP emissions scenarios or to plausible global warming levels. The NCA5 scenarios include two that are higher than the 95th percentile for the extreme emissions scenario RCP8.5 and include hypothesized ice sheet processes in which there is low confidence. Projections to 2050 require rates of sea level rise from 2025 to 2050 that are more than triple the rate observed during 2000-2024. Further, NCA5 ascribes *high confidence* to these sea level rise projections. CWG25 Section 7.3 provides further context for USGCRP projections of extraordinary sea level rise in the next 25 years.

More generally, NCA5's inclusion of, and even focus on, implausible extreme scenarios creates projections of alarming impacts that are very unlikely to be driven by anthropogenic warming.

7 Conflation of Natural and Anthropogenic Climate Changes

NCA5's Glossary defines "climate change" as a change in climate for any reason. This is technically correct, but at variance with the (now) popular perception of all climate changes being anthropogenic. The distinction is not academic- it is central both to attribution questions and to projections, since anthropogenic changes would respond to mitigation, while natural changes are unavoidable.

The discussion on NCA5 page 2-4 begins "Human activities are changing the climate", then goes on to list evidence for anthropogenic GHG emissions and climate warming. The next paragraph begins "Climate change is happening now in the United States. Including Alaska, the continental US has been warming about 60% faster than the planet as a whole since 1970." The implication is that the warming of CONUS faster than the planetary average is an effect of GHG emissions. But it is an artifact of the Earth's surface being 70 percent ocean. Since the ocean warms more slowly than land, comparison of any land surface outside the tropics with the global average would show the land surface to be warming faster than the global average, regardless of the cause of the warming.

The same page goes on to say "Climate change is already affecting people in the United States. Extreme heat was estimated to be responsible for more than 700 deaths per year between 2004 and 2018 although some estimates put heat-related mortality closer to 1,300 deaths annually." But extreme heat, whether natural or not, has always been a risk to human health. As to trends, the data show that adaptation has caused the mortality burden of extreme heat to drop substantially in recent decades (CWG25 Section 10.3.1).

Consider also the NCA5 statement on precipitation cited in Section 3.2:

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> Many eastern regions of the country are getting wetter (Figure 2.4). Average annual precipitation from 2002-2021 was 5%-15% higher relative to the 1901-1960 average in the central and eastern US, a trend attributable to climate change.

The attribution is superfluous because the statement is a tautology by NCA5's definition of climate change. But its gratuitous inclusion effectively attributes the observed trend to greenhouse gas emissions.

Exploitation of the ambiguity in "climate change" is endemic to NCA5. The NASEM review (pp. 23-24) commented on this problem as follows:

> The draft NCA5 report frequently describes "change" but does not consistently distinguish between natural variability and climate change. This lack of clarity can be misleading for the reader by creating the misconception that some impacts that are the result of the combination of natural variability and climate change are instead solely due to climate change... it is important for NCA5 authors to accurately identify the multiple drivers of change (including global change), in addition to climate change, and accurately attribute impacts. Clearly describing impacts due to natural variability, climate change, or a combination of the two is important not only for informing policy decisions, but also for building public understand and trust in the report's messages. Climate change and natural variability should be clearly defined in the glossary and natural variability could be introduced in chapter introductions when the concept is important for understanding key messages.

This could have been easily addressed, for example by reserving the term "climate change" for anthropogenic changes and using "climate variability" for natural changes. But the NCA5 authors seemingly ignored their recommendation.

A separate but related issue is use of the term "climate change" to refer to increases in socioeconomic vulnerabilities that have anthropogenic causes unrelated to GHGs. NCA5 page 1-19 states "Climate change exacerbates inequalities." But the issue discussed is the negative correlation between neighborhood-level income and land surface temperatures in urban areas. To the extent the correlation is real, the most likely explanation is that low-income households concentrate where housing is less expensive, which might be in neighborhoods with less nearby parkland and tree cover; that has nothing to do with CO_2 emissions.

8 Summary Evaluation of NCA5 and Recommendations for NCA6

This chapter summarizes our evaluation of NCA5 relative to OSTP's charge: whether NCA5 (1) complied with the USGCRP's statutory obligation; (2) adheres to the core tenets of Gold Standard Science; and (3) can suitably inform federal climate and energy policy. The points made in this summary analysis refer to specific sections of this report as well as to the CWG25 report.

8.1 Compliance with USGCRP's statutory obligation

As cited in Section 1.2 of this report, the Global Change Research Act requires an assessment that:

> (1) integrates, evaluates, and interprets the findings of the [Global Change Research] Program and discusses the scientific uncertainties associated with such findings;

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(2) analyzes the effects of global change on the natural environment, agriculture, energy production and use, land and water resources, transportation, human health and welfare, human social systems, and biological diversity; and
(3) analyzes current trends in global change, both human-induced and natural, and projects major trends for the subsequent 25 to 100 years.

We deem NCA5 to have fallen short when evaluated against these criteria because of the following major shortcomings (each is detailed in the sections and chapters cited):

- Inadequate assessment of the relevant topics in climate science and the hazard components of climate impacts (such as hurricanes and floods). NCA5 instead focuses on evaluation of societal vulnerabilities (such as flood infrastructure, access to air conditioning, etc.), "Climate Action," and policy recommendations with a social justice emphasis (Section 1.2).
- Overconfidence in conclusions and inadequate assessment of uncertainties (Section 3.1.5)
- Inadequate discrimination between natural and human-induced causes of trends and impacts (Chapter 7)
- Inadequate analyses of climate trends by relying on short time periods (Chapter 6)
- Uncritical evaluation of emission scenarios and climate model simulations in making projections for the next 25 to 100 years (Chapter 6; Section 3.2.1 and Chapter 5 of CWG25).

8.2 Adherence to the tenets of Gold Standard Science

With respect to the tenets of Gold Standard science listed in Section 1.2 of this report, we have identified the following major shortcomings in NCA5:

- **Lack of reproducibility.** In the few examples that we examined closely, we identified an instance where we could not reproduce the findings of the NCA5, a task that should require only rudimentary data analysis (Section 4.1)
- **Lack of transparency.** In many instances, the Traceable Account fails to justify the Key Finding. Metadata was not readily accessible. (Chapter 5)
- **Inadequate communication of error and uncertainty.** The Traceable Account for each Key Message provides a section on Major Uncertainties and Research Gaps; most of the accounts that we examined were superficial and uninformative. (Chapter 5)
- **Not skeptical of findings and assumptions.** The main text of the chapters is, with few exceptions, not skeptical of its findings and assumptions and does not mention dissent or disagreement. (Chapters 3 and 5)
- **Some hypotheses and Key Messages are not falsifiable.** Key Message 13.4 is but one of many examples: "Equitable Distribution of Transportation Trade-offs and Benefits Requires Community Involvement."
- **Failure to acknowledge benefits** of warming and additional atmospheric CO_2 (CWG25 Section 2.1, Chapter 9)
- **Inadequacy of the peer review process.** The review of the NCA5 Third Order Draft by National Academies of Science, Engineering and Medicine (NASEM) identified some of the deficiencies we have noted, but the NCA5 authors were not obligated to adopt the NASEM recommendations. More importantly, we've identified many other deficiencies in NCA5; the NASEM review did not point them out and thus lacked the rigor expected of NASEM reports.

8.3 Suitability for informing Federal climate and energy policy

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We assess that the selection and presentation of information in NCA5 makes it an unreliable basis for U.S. climate and energy policy making. For each of the elements of knowledge characterization suitable for risk management listed in Section 1.3, here are specific examples where NCA5 falls short:

- The degree to which the assumptions made are reasonable/realistic based on background knowledge
    - NCA5 focused on implausibly extreme scenarios for emissions and sea level rise and made policy recommendations without adequate consideration of the costs
- The degree to which data/information exists and are reliable and relevant
    - NCA5's unjustified assumptions about model reliability, and its use of short time periods for analysis, does not support its high-confidence conclusions
- The degree to which there is disagreement among experts, including those from different environments or academic fields
    - While NCA5 was an interdisciplinary effort, the concerns we have raised all point to a failure to canvass or communicate the full range of evidence, including data and research findings that speak against Key Messages.
- The degree to which the phenomena involved are understood and accurate models exist
    - NCA5 is not appropriately skeptical of the ability of climate models to attribute the causes of warming and extreme events or to project future climates, especially at the regional level
- The degree to which the knowledge has been thoroughly examined with respect to unknown knowns
    - A major NCA5 shortcoming is its dismissal of natural climate variability in many contexts where it should have been a major consideration

NCA5 is also problematic for informing policy because its exaggerated language promotes alarm and advocates for specific policies without a proper risk analysis. The NASEM Review of the NCA5 underscores the endemic nature of this problem - their review appears to be written by authors who share many of the biases of the NCA5 team, with an inordinate focus on social and policy issues. ~~It is then not surprising that objectivity can suffer when climate scientists communicate their understanding to non-experts. Further, the field of climate science has been politicized by NetZero mandates. This lack of objectivity usurps the public's right to make informed choices and undermines their confidence in the scientific enterprise.~~

~~Philip Handler, President of the National Academy of Sciences, identified the problem forty-five years ago in an~~ <u>editorial</u> ~~that still resonates:~~

> ~~Difficulty arises in the scientific community from confusion of the role of scientist *qua* scientist with that of scientist as citizen, confusion of the ethical code of the scientist with the obligation of the citizen, blurring the distinction between intrinsically scientific and intrinsically political questions. When scientists fail to recognize these boundaries, their own ideological beliefs, usually unspoken, easily becloud seemingly scientific debate.~~
> ~~[ALTHOUGH I VERY MUCH LIKE THIS TEXT, I THINK WE SHOULD DELETE IT IN AN EFFORT TO REMAIN CIRCUMSPECT]~~

NCA4 was a better policy-informing assessment than NCA5. It offered a more thorough consideration climate science, consistently used data back to 1901, and had less of an advocacy tone. But NCA4 is almost a decade out of date. More importantly, it shares NCA5's endemic problems of overconfident conclusions, inadequate treatment of natural variability, inadequate traceable accounts and communication of uncertainty, and over reliance on extreme scenarios.

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